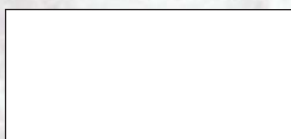


## Soil carbon monitoring using surveys and modelling

General description and application in the United Republic of Tanzania

This publication describes the application of survey- and modelling-based methods for monitoring soil organic carbon stock and its changes on a national scale. The report presents i) a design of the first inventory of soil organic carbon, including discussion on factors that affect the reliability of carbon stock estimates; and ii) a design of a modelling-based approach, including links to national forest inventory data and discussion on alternative soil organic carbon models. Both approaches can provide necessary information on soil carbon changes for a national greenhouse gas (GHG) inventory. A soil survey provides both an estimate of the stock of soil organic carbon when conducted for the first time and an estimate of the stock change when repeated. Dynamic soil carbon models provide an alternative for obtaining soil organic carbon estimates. Application and testing of soil carbon models typically require information about the amount and quality of litter input to the soil, the amount of carbon in different soils and the changes in the amount of soil carbon over time. Forest soils constitute a large pool of carbon and releases of carbon from this pool, caused by anthropogenic activities such as deforestation and forest degradation, may significantly increase the concentration of GHGs in the atmosphere. Therefore, estimating and reducing emissions from these activities have become timely issues. Currently, reliable estimates of soil organic carbon stock and stock changes are needed for REDD (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries) and GHG reporting under the United Nations Framework Convention on Climate Change (UNFCCC).



## Soil carbon monitoring using surveys and modelling

General description and application in the United Republic of Tanzania





# Soil carbon monitoring using surveys and modelling

General description and application  
in the United Republic of Tanzania

FAO  
FORESTRY  
PAPER

168

by

**Raisa Mäkipää,**

**Jari Liski,**

**Sabin Guendehou,**

**Rogers Malimbwi**

and

**Abel Kaaya**

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations (FAO) concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The mention of specific companies or products of manufacturers, whether or not these have been patented, does not imply that these have been endorsed or recommended by FAO in preference to others of a similar nature that are not mentioned. The views expressed in this information product are those of the author(s) and do not necessarily reflect the views of FAO.

All rights reserved. FAO encourages the reproduction and dissemination of material in this information product. Non-commercial uses will be authorized free of charge, upon request.

Reproduction for

resale or other commercial purposes, including educational purposes, may incur fees.

Applications

for permission to reproduce or disseminate FAO copyright materials, and all queries concerning rights and licences, should be addressed by e-mail to [copyright@fao.org](mailto:copyright@fao.org) or to the Chief, Publishing Policy and Support Branch, Office of Knowledge Exchange, Research and Extension, FAO, Viale delle Terme di Caracalla, 00153 Rome, Italy.

© FAO 2012

# Contents

Foreword	v
Acknowledgements	vi
Acronyms	vii
Executive summary	viii
<b>1. Introduction</b>	<b>1</b>
Need for soil carbon estimates	1
Soil carbon cycle	2
Challenges in monitoring changes in soil carbon	3
Methods of monitoring changes in soil carbon	3
Objective of this report	4
<b>2. Soil carbon monitoring based on repeated measurements</b>	<b>5</b>
Designing a soil carbon survey	5
Improving the efficiency of the sampling effort	5
Information needed to design a repeated soil carbon inventory	6
Between-site variation in soil carbon stock and number of plots to be measured	6
Within-site variation and determination of number of subsamples per plot	8
Uncertainties in soil carbon surveys	9
Sources of uncertainty	9
Sampling errors	9
Measurement errors	10
Quality control and quality assurance in soil carbon inventories	11
Need for consistency control	11
Soil sampling	11
Laboratory analyses	12
<b>3. Model-based soil carbon monitoring</b>	<b>15</b>
Model-based soil carbon monitoring system	15
Practical application of a model-based soil carbon monitoring system	18
<b>4. Evaluation of soil carbon monitoring methods</b>	<b>19</b>
<b>5. Soil carbon monitoring in the United Republic of Tanzania</b>	<b>23</b>
Soil organic carbon stock inventory in the United Republic of Tanzania	23
Background and rationale	23
NAFORMA sampling design	24
Sampling design in first soil survey	25

Soil sampling	27
Observations at a sample point	29
Compositing soil samples	29
Feasibility of the soil sampling design and its practical implementation	29
Measurements needed for designing a repeated soil carbon survey in the United Republic of Tanzania	31
Number of soil sampling plots to be measured	31
Within-site variation and determination of number of subsamples per plot	31
Model-based method	31
Overview of the task	31
Soil carbon model choice	32
Reliability of model-calculated soil carbon estimates	35
Spatial calculation units	35
Litter input and litter quality estimates	36
Climate data	37
Land-use change estimates	37
Initial soil carbon stock	37
Simulation of soil carbon changes	38
Local measurements to support the model application	38
Purpose of local measurements	38
Soil carbon pool	39
Litter decomposition and litter chemistry	39
Litter production	40
Recommendations for soil carbon monitoring in the United Republic of Tanzania	40
<b>References</b>	<b>43</b>

# Foreword

Rising levels of greenhouse gas concentrations in the atmosphere are predicted to alter the global climate pattern significantly, resulting in severe adverse effects on people's livelihoods, especially in Africa. An increase in the frequency of extreme weather events, such as tropical storms, droughts and persistently higher temperatures, has a direct impact on people's well-being, as these events reduce access to clean water and facilitate the spread of disease.

Forests play a major role in climate change. Nearly 20 percent of total anthropogenic greenhouse gas emissions result from changes within forests and changes from forest to other land uses in tropical countries. Therefore, limiting deforestation and forest degradation in the tropics is widely seen as an efficient means to mitigate climate change.

Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD) – a mechanism developed under the United Nations Framework Convention on Climate Change – is an effort to create a financial value for the carbon stored in forests, and thus provide incentives for developing countries to decrease deforestation and reduce carbon emissions from forested lands. To benefit from the REDD mechanism, countries need to be capable of reporting their forest carbon stocks and changes in these stocks over time.

One of the most important forest carbon stocks is forest soil. At the global level, the estimates of forest soil carbon stock vary from equal to twice that of forest vegetation. Because forest soils constitute such a large pool of carbon, releases from this pool, caused by deforestation, may significantly increase the concentration of greenhouse gases in the atmosphere.

Changes in soil carbon stocks over time can be estimated through repeated measurements or dynamic models. In both cases it is advisable to assess first the current stock through a carefully designed soil inventory. This study presents how to design such an inventory and discusses alternative approaches, including their advantages and drawbacks, to monitoring changes in soil carbon stock. In addition, it provides an example of a practical soil survey application, namely the soil carbon stock inventory of the National Forestry Resources Monitoring and Assessment project of the United Republic of Tanzania.

FAO's National Forest Monitoring and Assessment programme has developed multi-purpose and multi-source monitoring systems that have traditionally helped countries to assess their natural resources and manage them in a sustainable manner. Now, as illustrated in this paper, they also support designing and implementing REDD-compatible monitoring of forest carbon stocks and their changes. We hope that the example provided in the paper will help and encourage other countries to improve their capacity to assess and monitor their soil carbon stocks. This would help us all to understand better the role and potential of forest soils in the mitigation of climate change.

## Acknowledgements

The first draft of this publication was prepared by the authors, who worked under the coordination of FAO Forestry Officers Anssi Pekkarinen and Mikko Leppänen. The draft was then peer-reviewed by staff of the FAO Forestry Department and external reviewers, and a revised version was prepared by the authors, taking into account the inputs provided.

FAO sincerely thanks the authors for their dedication and the reviewers for their constructive feedback. Thanks are also extended to the personnel of the National Forestry Resources Monitoring and Assessment (NAFORMA) project of the United Republic of Tanzania and especially to its National Coordinator, Nurudin Chamuya, and its Chief Technical Advisor, Soren Dalsgaard, for their support during this process. Design and layout were done by Roberto Cenciarelli; Roberta Mitchell, Rebecca Obstler and Esther Phillips gave their support in the final editing and publishing of this work.



# Acronyms

<b>CDM</b>	Clean Development Mechanism
<b>COP</b>	Conference of the Parties (to the UNFCCC)
<b>GHG</b>	Greenhouse gas
<b>GPG</b>	Good practice guidance
<b>IPCC</b>	Intergovernmental Panel on Climate Change
<b>LULUCF</b>	Land use, land-use change and forestry
<b>NAFORMA</b>	National Forestry Resources Monitoring and Assessment
<b>QA</b>	Quality assurance
<b>QC</b>	Quality control
<b>REDD</b>	Reducing Emissions from Deforestation and Forest Degradation in Developing Countries
<b>UNFCCC</b>	United Nations Framework Convention on Climate Change

## Executive summary

The Intergovernmental Panel on Climate Change (IPCC) good practice guidance (GPG) defines five carbon pools that need to be monitored and reported as part of greenhouse gas (GHG) inventories, namely: above-ground biomass, below-ground biomass, litter, dead wood and soil carbon. Litter and soil are important carbon stocks. According to global assessments, soils contain two to three times as much carbon as the biomass or the atmosphere. As a result of the large carbon stock and active exchange of carbon dioxide with the atmosphere, soil can act as a major source of GHGs contributing to global climate change if carbon is released from soil to the atmosphere. Deforestation, forest degradation or changes in land management practices can cause releases of carbon from soil to the atmosphere. For these reasons, reliable estimates of soil organic carbon stock and stock changes are needed for REDD+ (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries) and GHG reporting under the United Nations Framework Convention on Climate Change (UNFCCC).

There are two principal approaches for estimating the stock and the stock changes of soil organic carbon, namely repeated soil surveys and modelling. A soil survey provides both an estimate of the stock of soil organic carbon when conducted for the first time and an estimate of the stock change when repeated. Dynamic soil carbon models provide an alternative for obtaining soil organic carbon estimates. Application and testing of soil carbon models typically require information about the amount and quality of litter input to the soil, the amount of carbon in different soils and the changes in the amount of soil carbon over time. Both approaches can form part of a national GHG inventory, and may be linked to national biomass inventories.

The objective of this report is to describe the application of survey- and modelling-based methods for monitoring soil organic carbon stock and its changes on a national scale. Examples of applying the methods are demonstrated in the United Republic of Tanzania, which represents a developing country in the tropics. The report presents i) a design of the first inventory of soil organic carbon, including discussion on factors that affect the reliability of carbon stock estimates; and ii) a design of a modelling-based approach, including links to national forest inventory data and discussion on alternative soil organic carbon models.

# 1. Introduction

## NEED FOR SOIL CARBON ESTIMATES

Increasing greenhouse gas (GHG) concentrations in the atmosphere create a threat to the global climate system and the environment. Soil is related to this issue since it can affect atmospheric carbon dioxide concentration by causing net emissions or acting as a sink of carbon.

Forest soils constitute a large pool of carbon and releases of carbon from this pool, caused by anthropogenic activities such as deforestation, may significantly increase the concentration of GHGs in the atmosphere (IPCC, 2000). Tropical deforestation represents nearly 25 percent of total anthropogenic GHG emissions worldwide (Pan *et al.*, 2011). Estimating and reducing emissions from these activities have become timely issues. Mechanisms that are effective in reducing emissions are of particular importance for the mitigation of global climate change.

Countries have agreed internationally to monitor their GHG emissions and removals. In accordance with Article 4.1(a) and 12.1(a) of the United Nations Framework Convention on Climate Change (UNFCCC), each Party (country) shall communicate to the Conference of the Parties (COP) to the UNFCCC a national inventory of anthropogenic emissions by sources and removals by sinks of all GHGs not controlled by the Montreal Protocol using comparable methodologies. The required contents of the national communications and the timetable for the submissions are different for Annex I and non-Annex I Parties. Annex I Parties (industrialized countries) that have ratified the Kyoto Protocol must also include supplementary information in their national communications and their annual inventories of emissions and removals of GHGs to demonstrate compliance with the Protocol's commitments. In addition, Annex I Parties are required to submit information on their national inventories annually, and to submit national communications periodically, according to dates set by the COP. The non-Annex I Parties (non-industrialized countries) must provide updated inventory reports every two years.

A framework for Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+ mechanism) has been designed to reduce emissions and enhance forest carbon stocks, following the agenda of the 15th session of the COP to the UNFCCC held in Copenhagen in 2009. The REDD+ mechanism also has the potential to promote co-benefits, including alleviating poverty, improving governance, conserving biodiversity and securing forest ecosystem services. Moreover, REDD+ is a framework that Annex I Parties can use to meet their commitments under the Kyoto Protocol of the UNFCCC, notably through Clean Development Mechanism (CDM) projects on afforestation

and reforestation. In the 2010 Cancun Agreements of the United Nations Climate Change Conference, the parties agreed to establish the Green Climate Fund, and projects aiming to decrease the rate of deforestation were accepted as CDM projects.

The soil carbon monitoring system will increase the ability of developing countries to enhance reporting in national communications to be submitted every four years to the UNFCCC as well as biennial reports with updates of national GHG inventories (UNFCCC decision 1/CP.16). It will assist countries to report on eligible activities under the REDD+ mechanism, including reducing emissions from deforestation and forest degradation; conservation of forest carbon stocks; sustainable management of forests; and enhancement of forest carbon stocks (UNFCCC decision 1/CP.16).

The methods for soil carbon monitoring given in this paper are useful tools for estimating soil carbon pools in constructing the national forest reference emission level (UNFCCC decision CP.17).

## SOIL CARBON CYCLE

Soil plays an important role in the global carbon cycle. The carbon stock of soil equals some 1 500 Pg in the topmost 1 m soil layer (Eswaran, van den Berg and Reich, 1993; Jobbágy and Jackson, 2000), and approximately 506 Pg (32 percent) of this is in the tropics (Eswaran, van den Berg and Reich, 1993) and 160 Pg in Africa (Henry, Valentini and Bernoux, 2009). Globally, the soil carbon stock is nearly three times the amount in the above-ground biomass and about twice as large as the carbon stock of the atmosphere (e.g. Eswaran, van den Berg and Reich, 1993). In Africa, the soil organic carbon stock corresponds to 68 percent of the terrestrial carbon stock (Henry, Valentini and Bernoux, 2009). Carbon dioxide emissions resulting from the decomposition of organic carbon compounds in soil amount to 60–80 Pg carbon per year (e.g. Thum *et al.*, 2011). A somewhat similar amount of carbon is brought annually to soil in the form of plant residues. These carbon fluxes from and to the soil are seven to nine times as large as the current anthropogenic fossil carbon dioxide emissions to the atmosphere, equal to 9.1 Pg in 2010 (Peters *et al.*, 2012).

Changes in soil carbon result from an imbalance between the carbon fluxes into and out of the soil. When more carbon is brought to the soil than is released, carbon accumulates in the soil, and vice versa. Increments in plant productivity and input of plant residues to soil thus have an increasing effect on soil carbon stock, whereas more favourable conditions for decomposition have a decreasing effect. Land-use change may induce quite rapid changes in soil carbon as a result of altered carbon input to the soil or decomposition conditions or both (e.g. Post and Kwon, 2000; Vågen, Lal and Singh, 2005; Zingore *et al.*, 2005).

## CHALLENGES IN MONITORING CHANGES IN SOIL CARBON

Typically, the soil carbon stock is large and small relative changes may have a remarkable influence on forest carbon balance. In tropical rain forests, soils contain nearly as much carbon as vegetation, but exceed the biomass in other ecosystems by a factor of two to ten (Sombroek, Nachtergaele and Hebel, 1993). The carbon stock of tropical soils is smaller than the global average, but the soil carbon turnover rate is very high (Raich and Schlesinger, 1992; Cao and Woodward, 1998), which underlines the importance of monitoring tropical soils as a part of global carbon balance. It is a challenging task to detect a change in a large stock, especially in the case of forest soils where between-site and within-site variations are considerable (Conen, Yakutin and Sambuu, 2003; Yanai *et al.*, 2003; Wang *et al.*, 2009; Häkkinen, Heikkinen and Mäkipää, 2011). Henry, Valentini and Bernoux (2009) reviewed soil organic carbon estimates reported for Africa and concluded that only a few precise country- or regional-scale studies exist. Because of the variation in soil properties, e.g. in the soil carbon stock, a large number of samples are required in order to provide soil carbon estimates that are accurate enough for monitoring purposes.

## METHODS OF MONITORING CHANGES IN SOIL CARBON

Under the UNFCCC, countries must estimate and report GHG emissions and removals, including changes in carbon stocks in all five pools (above- and below-ground biomass, dead wood, litter and soil carbon) and associated emissions and removals from land use, land-use change and forestry activities according to the GPG (IPCC, 2003; 2006).

Earlier global efforts on soil studies have – to a large extent – been focused on assessment of soil properties including carbon stock rather than on soil carbon changes (Batjes, 1995; FAO, 1995; 2006; FAO/IIASA/ISRIC/ISSCAS/JRC, 2008). IPCC (2003; 2006) has developed standard methods for estimating soil organic carbon stocks and stock changes. These methods are characterized by flexibility, ranging from the Tier 1 default method prescribed by IPCC with fixed default values, to methods that incorporate local information to estimate carbon stock changes at Tier 2 level, and to more advanced modelling and measurement-based networks at Tier 3 level. Features of the tiers as well as their applicability and associated weaknesses are evaluated and discussed in detail by Smith *et al.*, 2012. Some developed countries have established or are planning to establish representative networks of sample plots for repeated measurements of soil carbon stock (e.g. Ståhl *et al.*, 2004). Since measuring soil carbon stock changes is a laborious and expensive undertaking (Mäkipää *et al.*, 2008), soil carbon modelling is often used as an alternative or a complement to repeated soil carbon inventories to estimate and report the changes in soil carbon stock (Peltoniemi *et al.*, 2007). However, if the pool is not a significant contributor (less than 5 percent) to the GHG balance, emission and removals can be assessed using the Tier 1 default value. On the other hand, when the soil compartment is considered to be a significant source of GHG emissions, accuracy of the method needs to be improved.

**OBJECTIVE OF THIS REPORT**

The objective of this report is to describe and evaluate methods to monitor soil carbon at national level. Two kinds of methods are described: field surveys and modelling-based methods. In addition to general descriptions, the application of both methods is described in specific detail for the United Republic of Tanzania.

## 2. Soil carbon monitoring based on repeated measurements

### DESIGNING A SOIL CARBON SURVEY

The objective of the nationwide soil carbon inventory is to provide unbiased estimates of the soil carbon stock and stock changes. In designing soil carbon monitoring, relevant issues to be considered are:

- sampling intensity (number of study sites) and rules to locate the study sites
- sampling interval (e.g. decadal or five-year interval)
- soil layers to be studied
- location of sample points and their number at the study sites

Constructing a sampling design is an optimization problem, where the trade-off is between required resources and reliability of resulting estimates. When planning sampling to detect a potential change, it is necessary to know how many samples need to be taken in order to estimate a statistically significant change. Appropriate sampling intensity (sample size) and sampling interval (time between consecutive measurements) can be designed after collecting information on between-site variation and estimation of the rate of potential change. Efficiency of the sampling can be improved by stratification, if prior information on the variation of the target variable is available.

Selection of the soil layers to be studied can be guided by the known sensitivity of different layers to human-induced disturbances. The 2006 IPCC guidelines recommend using a default 0–30 cm layer. Within this layer, the influence of management practices is more pronounced than in the deeper soil layers (Bationo *et al.*, 2007). Knowledge of within-site variation of soil properties can be used to determine the number of subsamples per plot.

Soil samples that are taken and prepared for soil organic carbon analyses can also be used for the measurements of other soil variables (e.g. soil nutrients, pH and grain size distribution). Since many soil properties are related, for example, to site productivity and site protection from erosion, an evaluation should be made as to which measurements are feasible and how/where samples can be stored for additional analyses in the future.

### IMPROVING THE EFFICIENCY OF THE SAMPLING EFFORT

The efficiency of soil carbon monitoring can be improved and costs reduced by stratified sampling. Stratification increases efficiency if a subdivision of the population is made so that within-stratum variability is lower than the variability within the entire population.

Stratification by land-use category, soil type, etc., i.e. by groups where rates of soil carbon change are similar, will improve efficiency of the sampling targeted for soil carbon monitoring. A target variable in the soil carbon monitoring is a change in the soil carbon stock, but there is far less information on spatial variation of soil carbon changes than on soil carbon stock (Häkkinen, Heikkinen and Mäkipää, 2011). Therefore, information on the variation of carbon stock (or other measured soil variables) may be used for sampling design, but such information on stocks cannot be used for stratification since large soil carbon stocks do not necessarily indicate major changes.

It has been estimated that, by grouping similar sites (in terms of model-predicted change in the soil carbon stock) into the same stratum, and optimally allocating samples to these strata (according to the size and variance of the strata), the number of plots can be decreased by 25 percent without a reduction in the precision of the estimates (Peltoniemi, Heikkinen and Mäkipää, 2007). The gain provided by stratification is, however, sensitive to uncertainties in the predicted changes (e.g. those resulting from future thinning activities) and precision of the measurements. Furthermore, stratification with the target of soil carbon monitoring may result in an allocation of the sampling effort that is less effective for assessment of other soil parameters than simple random sampling (Peltoniemi, Heikkinen and Mäkipää, 2007).

## INFORMATION NEEDED TO DESIGN A REPEATED SOIL CARBON INVENTORY

### Between-site variation in soil carbon stock and number of plots to be measured

In designing soil monitoring, information on between-site variation of soil properties can help decide upon the total number of plots to be measured. The first round of a nationwide soil carbon inventory will yield information on the between-site variation of soil carbon stock that can be used to estimate the number of plots allowing detection of change after a repeated inventory.

The number of plots needed for detection of a change in the soil carbon stock is estimated using the equation:

$$n = (t \times s / E)^2 \quad (1)$$

where  $n$  is the number of sample plots required,  $t$  is a value taken from the student's  $t$  distribution table for a given number of degrees of freedom and desired confidence interval,  $s$  is the estimated standard deviation of the measured values (assuming independency of the observations), and  $E$  is the desired half of the confidence interval. This is a general formula that applies when soil carbon stock measurements have a normal distribution.

The desired confidence interval of a carbon stock estimate should allow detection of the expected change in the soil carbon stock. In general, the rate of soil carbon change is not known, but can be estimated with soil modelling (e.g. Liski *et al.*, 2006) or generalized from CO<sub>2</sub> flux measurements of selected sites

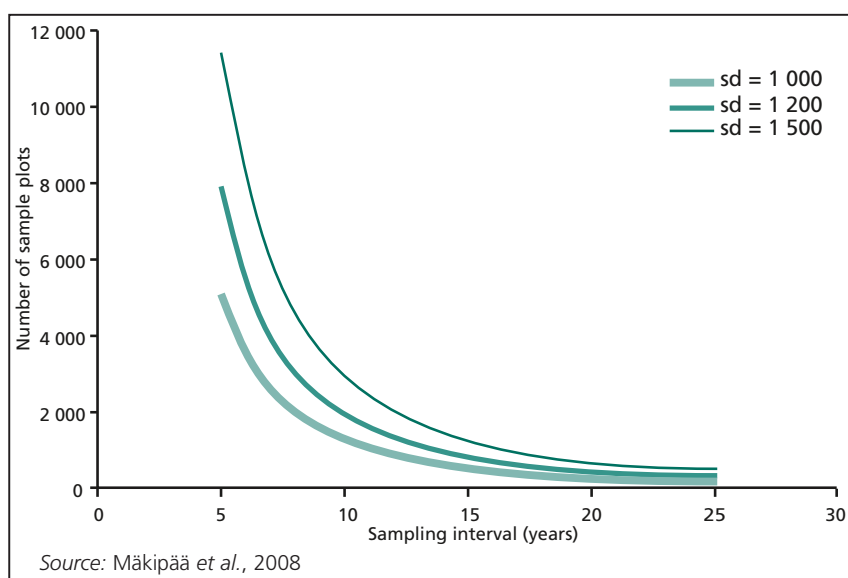


(e.g. Malhi and Grace, 2000). If we assume that the average rate of change is  $11 \text{ g C m}^{-2} \text{ yr}^{-1}$  (as has been predicted by soil modelling in a country-scale assessment by Liski *et al.* [2006]), the desired half of the confidence interval of the carbon stock estimate (E) is  $27.5 \text{ g C m}^{-2}$  with a sampling interval of five years, increasing to  $137 \text{ g C m}^{-2}$  with extension of the sampling interval to 25 years (assuming that the carbon change increases linearly over time) (Mäkipää *et al.*, 2008). In disturbed forest soil under high anthropogenic pressure, temporal variation of soil carbon stock might be high and linear trends non-existent. In such cases, detection of the change with repeated measurements is possible only with very short sampling intervals.

We can assume a standard deviation of  $1\,000 \text{ g C m}^{-2}$  (which is the value reported for the mean carbon stock of the uppermost soil layers by Peltoniemi *et al.* [2004]), and also apply values of  $1\,250$  and  $1\,500 \text{ g C m}^{-2}$  in order to determine the sensitivity of the results to this assumption. With these assumptions, the approximate estimate for the minimum number of sample plots required to detect a change in this soil layer is  $3\,000$  plots with a sampling interval of ten years (Figure 1). This sampling intensity allows detection of an expected change of  $110 \text{ g C m}^{-2}$  per ten years if the standard deviation of the measured carbon stock is less than  $1\,500 \text{ g C m}^{-2}$ . With a local representative estimate for variation of soil carbon stock (standard deviation of mean carbon stock) and prediction of the rate of soil carbon change, this calculation can be updated for a target region or country.

FIGURE 1

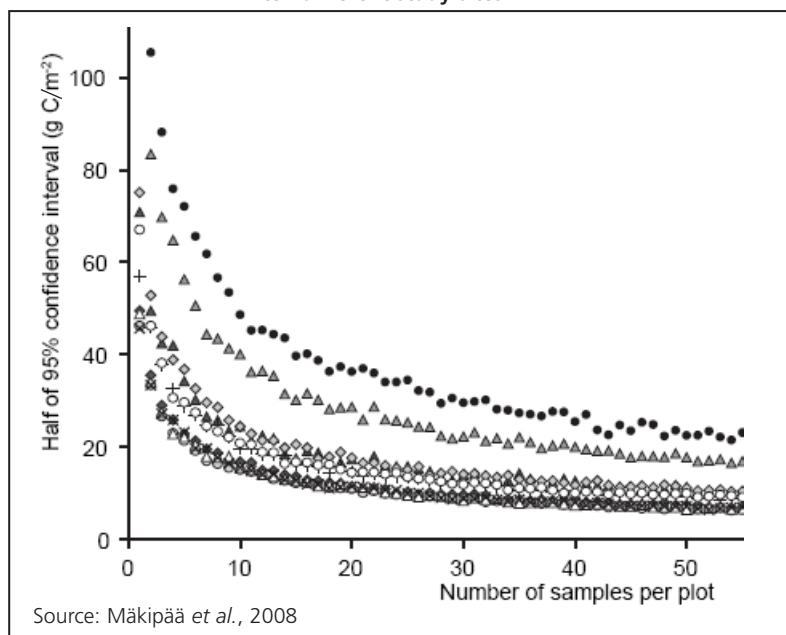
Sample size required with different sampling intervals calculated on the assumption that the change to be detected is  $11 \text{ g C m}^{-2}$  per year. Standard deviation (sd) of measured carbon stock was assumed to be  $1\,000 \text{ g C m}^{-2}$ . Larger values ( $1\,250$  and  $1\,500 \text{ g C m}^{-2}$ ) were applied to show the sensitivity of the results to this assumption



### Within-site variation and determination of number of subsamples per plot

Knowledge of the within-site variation in the soil carbon stock is used to determine the number of subsamples per plot yielding estimates that are accurate and precise enough for monitoring purposes. The accuracy of the mean estimate increases with the number of samples per plot. For instance, in a study focused on within-site spatial variation of the carbon stock of the organic layer, 73–116 samples were taken with a soil corer at ten study sites (Muukkonen, Häkkinen and Mäkipää, 2009). The authors' results indicate that required accuracy is usually obtained with 10–20 samples per plot, after which increases in the sample size do not significantly increase accuracy (Figure 2).

FIGURE 2  
Confidence intervals of the carbon stock of the organic layer according to sample size for ten different study sites



The appropriate number of subsamples can be determined in a case study where plots are sampled in more detail and each of the collected samples is analysed separately. Thereafter, determined sample size per plot can be adopted for an operationalized soil inventory, where soil samples taken from the same plot and same soil layer can be pooled to reduce the costs of laboratory analyses. However, the use of pooled samples (one sample analysed per layer per plot) means that information on the within-site variation is lost and it is difficult to determine when the difference between two measurements is significant at plot scale. Despite these drawbacks, the pooling is efficient and accepted in regional and national soil surveys aimed at assessing change in the mean carbon stock.

## UNCERTAINTIES IN SOIL CARBON SURVEYS

### Sources of uncertainty

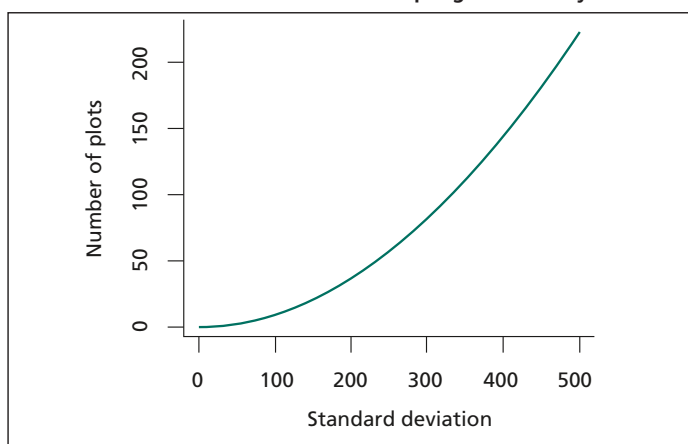
The possibility of deriving uncertainty estimates based on a formal statistical procedure is an important advantage in applying a sample-based inventory. This section describes the different sources of error in soil surveys and their effects on overall uncertainty in soil carbon estimates. The major types of error in a soil carbon inventory are those of sampling and measurement. In addition, model errors, classification errors in upscaling (e.g. plots recorded as afforested grassland misclassified to grassland during the processing of the data) as well as registration and calculation errors may be potential sources of uncertainty in a sample-based inventory (IPCC, 2003). Furthermore, inclusion of data from outside the population (e.g. plots located on land that is not among the target land-use categories) or sampling that does not include some elements of the population (e.g. ignoring the organic layer) may cause errors.

### Sampling errors

Sampling is a practice that is used to select a subset of objectives within a population in order to yield some knowledge (e.g. soil carbon amount) about the population of concern, since it is not feasible to measure the entire population. In soil carbon inventories, systematic sampling is most commonly applied, since it is effective and easy to implement. However, efficiency of the sampling can be improved and sampling errors reduced with stratification if a priori information on target variable is available. Using proper sampling design (random or systematic, stratified or non-stratified), sampling errors are only random and can be reduced by increasing the sample size, which results in greater precision. On the other hand, heterogeneous soils require a larger sample size to reach a degree of precision that is adequate for detection of a change by repeated measurements (Figure 3).

FIGURE 3

**Number of sample plots needed for detection of soil carbon change by variation (sd of soil carbon stock change  $\text{g C/m}^2$ ) when the amount of change is assumed to be  $400 \text{ g C/m}^2$  between initial and second sampling of a soil layer**



The uncertainty estimates derived with sampling principles for sample-based variables can be combined with the uncertainties of other data sources and models using error propagation equations (e.g. IPCC, 2003).

### Measurement errors

Measurement errors can lead to substantial systematic errors, especially where changes are estimated by repeated measurements and the systematic error levels and direction vary over time. The size of measurement errors can only be estimated by careful control measurements on a subsample of the plots (e.g. 1/20 of the sites/samples/elements re-measured with careful control measurements). Furthermore, in some cases it is possible to obtain true measurement values through highly accurate control procedures, e.g. potential systematic errors in the carbon content derived with wet combustion can be checked by more accurate carbon analysis of the very same samples with a dry combustion analyser (where products of combustion are measured using a thermal conductivity detector). Potential sources of measurement errors considered in this report are soil density measurement; determination of depth of soil sample collection; errors introduced by incorrectly calibrated laboratory instruments; and systematic errors introduced by incorrectly calibrated methods of carbon analysis in participating laboratories.

In soil carbon stock and stock change measurements, errors in soil density measurements are typical sources of uncertainty. Since both carbon content and soil density vary across soil profiles, volume-specific soil samples need to be taken from all soil layers that are accounted for. A volume-specific cylinder is the recommended sampling device and it is important that sampling be carried out extremely carefully, i.e. the cylinder is filled properly. In the case of challenging soil texture such as stone-packed coarse soil or compact clay soil, it may be necessary to use a smaller cylinder, but the volume of the cylinder should be recorded to allow accurate estimates of the soil carbon amount ( $\text{g C/m}^2$ ).

In general, soil carbon concentration decreases with soil depth and for detection of the soil carbon stock change it is important that soil samples of consecutive inventories represent the same soil layers. If the soil sampling layer is determined to be, for example, the topmost 30 cm, the soil samples may cover the entire profile down to 30 cm (e.g. samples from the organic layer and 0–10 cm, 10–20 cm, and 20–30 cm mineral soil layers) or they may be point samples and the change in the soil carbon concentration between sample points is interpolated or modelled. The soil sampling procedure in the first sampling and in consecutive samplings should be as similar as practicable.

Laboratory measurements may be a major source of error, if necessary calibration and testing of the methods are not carried out. A key instrument is balance, which needs to be calibrated according to the guidelines and calibration sets provided by the manufacturer. Since precision of the balance has to be high enough for the intended measurements, it is recommended recording precision as given in the documentation of the used balance in data files.

For the determination of soil organic carbon various methods can be used. A common method is to determine organic matter content by loss of ignition and to convert that into carbon concentration by using the van Bemmelen conversion factor, which assumes that soil organic matter is 58 percent carbon. Another option for the determination of organic matter is the wet-chemical oxidation technique (Walkley-Black, or a modification), but this requires the use of potassium dichromate, and disposal of the waste is problematic. Furthermore, it may not measure all the organic carbon, but only an easily oxidized part. A more accurate carbon estimate can be obtained with a dry combustion analyser that gives carbon (and nitrogen) concentrations directly. High-temperature dry combustion can be used as a standard against which other techniques are calibrated. All methods have potential for major errors in sample preparation, in the determination of moisture content of samples and in the performance of the method itself. To avoid biased results, it is necessary to calibrate the method and to check the consistency of the analysis performed in the different laboratories and at different times. This can be done by analysing samples with known carbon concentration as test samples. Any significant deviation of reference concentration will lead to necessary repair or calibration of the instrument.

## **QUALITY CONTROL AND QUALITY ASSURANCE IN SOIL CARBON INVENTORIES**

Quality control (QC) is a system of routine technical activities to assess and maintain the quality of the inventory as it is being implemented. It is carried out by personnel implementing the inventory. Quality assurance (QA) is a planned system of review procedures conducted by personnel not directly involved in the inventory. Reviews, preferably by independent third parties, are undertaken upon a completed inventory following the implementation of QC procedures (IPCC, 2006). The objective of the QC/QA process is to increase and ensure the credibility of the soil carbon inventories.

### **Need for consistency control**

Differences in soil sampling, sample preparation and procedures of chemical analyses can introduce considerable systematic errors in soil carbon estimates. The resulting soil carbon stock estimates may be biased and change estimates may be invalid if level and direction of error vary over the monitoring period. Major systematic errors can occur in cases where an estimate is based on a population that is different from the population where the estimate is to be applied (i.e. biased or statistically non-representative sampling).

### **Soil sampling**

At the time of establishment of a network of monitoring plots, it is essential that recording of land-use category, human activities, natural vegetation type and soil type as well as procedures to select plots to be sampled are consistent across the sampled population. In consecutive inventories, the same rules and delineations of

the sampled population (e.g. land-use categories to be included) must be followed. For instance, if urban areas are excluded from the soil inventory and a potential sample plot is located in land that is turning from urban into forest land, which is accounted for in the sampling population, a new plot needs to be established in the second inventory.

Delineation of soil layers (organic versus mineral soil) and determination of soil sampling locations in the soil profile (depth from soil surface) have to be consistent across the entire country in nationwide inventories. Since the topmost layer has a higher carbon content than the deeper soil layers, slight differences in sampling depth may introduce high systematic errors. This is a considerable source of uncertainty in soil carbon monitoring and can be minimized only by careful fieldwork. A continuous soil sample, which starts from the soil surface and reaches down to the selected depth, would be optimal to avoid errors in the location of the sampling layer, but such samples are extremely difficult to obtain from compact or stony soils. Therefore, an approach where representative samples from different soil depths are taken is recommended.

In cases where it is not possible to follow a sampling protocol, deviations should be recorded and documented with necessary details on data forms in order to ensure correct calculations. Consistency of the sampling can be tested by repeated measurements, i.e. cross-checking by another field team repeating all measurements (without knowing the data collected by the first team), but it is not possible to obtain duplicated soil samples for comparison from the very same location.

#### *Checklist for QC/QA activities of field measurements*

- Check for consistency of procedures to select plots across sampled population; follow the same rules during entire inventories and consecutive inventories.
- Check that plots have been installed and measured correctly, by having approximately 10 percent of all plots re-measured by an independent team. If the deviation between measurement and re-measurement is greater than 5 percent, investigate the source of the error, record and correct.
- Check for consistency of the soil layers to be sampled.

## **Laboratory analyses**

### *Consistency checking between laboratories before they start processing soil samples*

A detailed protocol of sample preparation and laboratory analyses needs to be prepared in order to obtain consistent results if analyses are carried out in different laboratories. In addition, it is necessary to analyse a set of test samples in all participating laboratories. In practice, soil samples that represent a range of different soil types are taken and homogenized in one laboratory. A homogenized soil sample is then divided into identical subsamples, which are analysed in participating laboratories according to a common protocol. Results of the analyses are reported to the coordinating laboratory where the consistency of the

participating laboratories is checked. Should the results submitted by a laboratory deviate from the accepted mean value, they will fail the test and cannot participate in analyses of the real samples until they are able to reach an acceptable level of consistency with other laboratories.

Should laboratories apply different methods in carbon analysis, calibration of the methods is necessary and the dry combustion technique should be used as a standard against which other techniques are calibrated.

#### *Test/calibration samples to be analysed during processing of soil samples*

After initial checks of the participating laboratories, QC of the laboratories needs to be continued by regular analyses of the test samples. These samples can be identical subsamples of a large soil sample with known carbon content. The samples distributed to each of the participating laboratories are analysed at regular intervals with other soil samples. Should results deviate from earlier analyses and from “known values”, the procedure must be checked and sources of the errors eliminated.

All measurements should be conducted in laboratories where QC practices are well understood and followed. Standard laboratory practices include documentation of sample handling and preparation before analyses, procedures for all analyses, sample storage after analysis, and calibration of instruments. In addition, participating laboratories are expected to report implementation of QC techniques, including replicate samples of standard analyses, internal QC samples, and reference samples of the nationwide soil survey.

#### *Checklist of QC/QA activities of laboratory analyses*

- Adhere to protocol of sample preparation and laboratory analyses at all times.
- Conduct laboratory analyses for replicate samples and check results.
- Cross-check results of analyses by another laboratory and explain any differences identified.
- Calibrate methods if methods vary across laboratories.

#### *Checklist of QC/QA activities of data entry and analyses after laboratory measurements*

- Cross-check a sample of input data for transcription errors.
- Ensure that all files are named appropriately.
- Check that units are properly labelled.
- Check for consistency among time-series data; identify outliers as soon after the actual measurement as possible and investigate the causes of the outlying observation, and correct if needed.
- Compare estimates from field measurements and laboratory analyses with literature values.
- Review the entry of data into the data analyses spreadsheets by an independent verification.





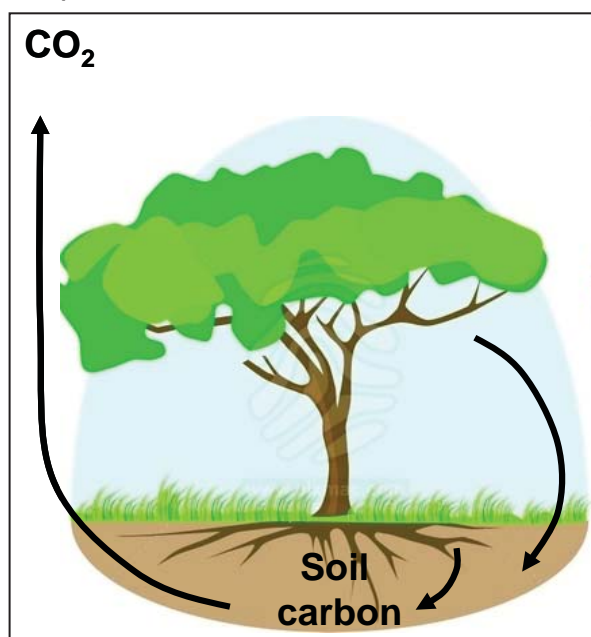
### 3. Model-based soil carbon monitoring

#### MODEL-BASED SOIL CARBON MONITORING SYSTEM

A model-based soil carbon monitoring system consists of a model of soil carbon, input data to the model and results on soil carbon calculated (Figure 4). This basic structure is similar between systems although details may vary (e.g. Kurz *et al.*, 1992; 2009; Post *et al.*, 2001; Liski, Perruchoud and Karjalainen, 2002; Liski *et al.*, 2006; Lagergren *et al.*, 2006; Ogle and Paustian, 2005). Input of carbon to soil over time is estimated based on biomass information. Cycling of carbon in soil is simulated using the soil carbon model. As a result of this simulation, estimates are obtained for the components of the soil carbon budget, such as i) the carbon pool of soil; ii) changes in the carbon pool of soil over time; and iii) carbon dioxide emissions from soil as a result of decomposition of organic carbon compounds in soil (heterotrophic soil respiration).

FIGURE 4

A schematic presentation of a model-based soil carbon monitoring system. Input of carbon to soil is estimated based on biomass information. Cycling of carbon in soil is simulated using a soil carbon model. Results are obtained for the carbon pool of soil, changes in the carbon pool of soil over time and soil carbon dioxide emissions



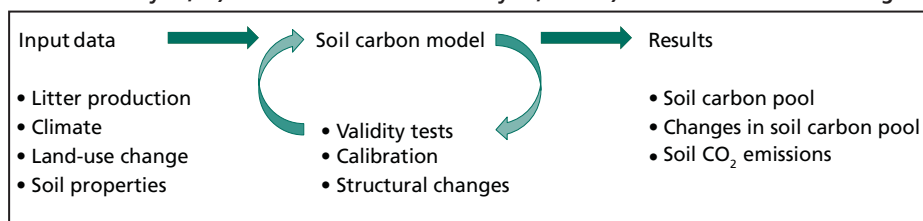
The soil carbon models used in model-based soil carbon monitoring systems are generally dynamic rather than static models. The essential difference between these model types is that the dynamic models account for the element of time, unlike the static models. The dynamic models are considered to be more suitable for simulating carbon cycling in soil, because the carbon pool of soil consists of different age classes and these classes may respond to changes in conditions in different ways. Consequently, changes in the carbon pool of soil do not depend only on conditions at a particular moment but also on conditions in the past. The dynamic models are able to account for this behaviour, whereas the static models are not. It is worth pointing out that the simplest IPCC Tier 1 and 2 methods, commonly applied when there is only limited information, are based on static models (emissions factors or soil carbon contents by land-use category, etc.), whereas an application of a dynamic model belongs to a more advanced Tier 3 methodology in the current IPCC classification.

There are already established dynamic soil carbon models that can be used and have been used as parts of model-based soil carbon monitoring systems, such as CENTURY (Parton *et al.*, 1987); RothC (Coleman and Jenkinson, 1996); SOILN (Eckersten and Beier, 1998); ROMUL (Chertov *et al.*, 2001); Yasso or Yasso07 (Liski *et al.*, 2005; Tuomi *et al.*, 2009; 2011). From the point of view of a user, these models differ from each other in complexity and requirements of input information (Peltoniemi *et al.*, 2007). The complex models need more complicated and more detailed input information than the simple models. Yasso07 and RothC (Coleman and Jenkinson, 1996) are examples of simple soil carbon models requiring only basic input data, whereas CENTURY and ROMUL represent more complicated soil carbon models with more demanding input data requirements.

The input data used by the soil carbon models consist of the most important variables affecting carbon cycling in soil (Figure 5). These variables are commonly i) litter production of vegetation representing the quantity and quality of carbon input to soil; ii) temperature and moisture affecting the decomposition rate of organic matter in soil; and iii) soil characteristics, such as texture, affecting stabilization of organic matter in soil and controlling soil moisture conditions. In addition, whenever land-use change is an important factor affecting soil carbon, it is essential to account for land-use change effects in a model-based soil carbon monitoring system.

FIGURE 5

**An application of a model-based soil carbon monitoring system consists of four components: i) input information to a soil carbon model; ii) reliability control of modelling soil carbon cycle; iii) simulation of soil carbon cycle; and iv) results of soil carbon budget**



In practice, when choosing a soil carbon model to be used in a model-based soil carbon monitoring system, it is usually necessary to make a compromise between the complexity of the soil carbon model and the availability of the input data (Peltoniemi *et al.*, 2007). The input data required by the complex models may not be available and, for this reason, it may be necessary to use a simpler model. Still, to be useful, the simple model must account for the heterogeneity of conditions in the region of application adequately and be able to describe the effects of the most important factors affecting soil carbon. Only then can the results of the model-based soil carbon monitoring system be reliable and the system able to capture the basic variability of soil carbon pools and the main trends of change in the pools.

An important step in applying a model-based soil carbon monitoring system is an evaluation of the reliability of the results (Figure 5). Information on reliability can be obtained by comparing the results given by the system with measured data. Useful measurements to be used in such a reliability evaluation (including systematic and random error) include data on soil carbon pools, soil carbon changes and decomposition rate of litter or soil carbon.

If it appears that the results of the model-based soil carbon monitoring system deviate from the measurements, the measurements can be used to improve the monitoring system. The data can be used to recalibrate the system or even to modify the structure of the system to make it more suitable for the particular application.

The reliability of results obtained using a model-based soil carbon monitoring system can be estimated in a statistical sense at the scale of the application (landscape, country) provided that uncertainty about the input data to the soil carbon model and the parameter values of the soil carbon model are known. Unfortunately, little attention has been paid to statistical uncertainty about the parameter values of soil carbon models when these models have been developed. Consequently, statistical uncertainty estimates are not available for the parameter values of most soil carbon models. In the absence of the statistical uncertainty estimates, it is still possible to analyse the sensitivity of the results of a soil carbon model to changes in the parameter values. However, it is then not possible to estimate the reliability of the results in a statistical way. When statistical uncertainty estimates are available for the parameter values of a soil carbon model, it is possible to give statistical uncertainty estimates for the results of the model, provided that reliable uncertainty estimates are also available for the input data to this model.

In conclusion, the components of a model-based soil carbon monitoring systems exist and these systems provide a feasible and practicable means to monitor soil carbon. Consequently, model-based systems provide a viable alternative or complement for surveys to monitor soil carbon.

## **PRACTICAL APPLICATION OF A MODEL-BASED SOIL CARBON MONITORING SYSTEM**

In order to apply in practice a model-based soil carbon monitoring system on a national or regional (subnational) scale, it is first necessary to form an overall picture of the task. This involves i) gathering general information about the region in relevant aspects such as vegetation, climate, natural disturbances and management of ecosystems; ii) finding out the availability of input information to the model-based soil carbon monitoring system; iii) deciding upon the time period that the calculations will cover; and iv) finding out the availability of information to test the validity of the system.

After an overall picture has been gained, application of the model-based soil carbon monitoring system can be divided into the following practical steps:

- 1) choice of the soil carbon model to be used
- 2) reliability control: evaluation and possible improvement of the soil carbon model to be used in the application

Steps 1 and 2 result in a suitable soil carbon model for the application.

Deciding or bringing together

- 3) spatial (geographic) calculation units
- 4) litter input data (quantity and quality)
- 5) climate data
- 6) land-use change data

Steps 3 to 6 result in input data by the spatial (geographic) calculation unit of the application.

- 7) determination of initial soil carbon pools to be used in the calculations
- 8) simulation of soil carbon cycling in the region of the application over the study period

Steps 7 and 8 represent the actual soil carbon calculations and give results of the soil carbon budget, namely the pool of soil C, changes in the pool of soil carbon over time and emissions of carbon dioxide from the soil.

## 4. Evaluation of soil carbon monitoring methods

There is a timely need for soil carbon monitoring in developing countries, and the monitoring system to be applied needs to agree with instructions given by the Intergovernmental Panel on Climate Change (IPCC). UNFCCC decision 2/CP.13 encourages Parties not included in Annex I to the UNFCCC (i.e. non-industrialized countries) to use the most recent reporting guidelines as set out in UNFCCC decision 17/CP.8 as a basis for reporting GHG emissions from deforestation and to apply the IPCC guidelines for land use, land-use change and forestry (GPG LULUCF).

Currently, the majority of the non-Annex I Parties uses the IPCC default assumption that there are no changes in soil carbon. Given that soil carbon is a significant carbon pool, it is critical to estimate stocks and changes, using higher tier methods in line with IPCC GPG LULUCF. Both the repeated soil surveys and the model-based method described in this report are considered higher tier methods as described in GPG LULUCF. The use of a higher tier method improves estimates of carbon emissions and removals, following the principles of transparency, accuracy, completeness, consistency and comparability compared with the default method.

Given that reductions in emissions or increases resulting from the demonstration activity should be based on historical emissions, taking into account national circumstances (UNFCCC decision 2/CP.13), there is an urgent need in developing countries to establish a national monitoring system to facilitate the development of a historical emission reference scenario and future emission levels. The principles of completeness and accuracy are particularly challenging since the applicability of the model-based method has not yet been thoroughly tested in the majority of tropical countries and repeated soil carbon measurements are almost non-existent.

Both the soil survey method and the model-based method have advantages and disadvantages when applied to soil carbon monitoring.

### *Soil survey method*

#### *Advantages*

- Improve estimates of changes in carbon stocks of soil and estimates of emissions/removals associated with these changes in line with IPCC GPG LULUCF and UNFCCC reporting requirements compared with the default method.
- Produce transparent estimates that can be reported consistently over time.
- Sampling design and soil measurements can be coordinated with inventories of land-use and biomass resources.

- There are well-established statistical procedures to estimate uncertainties.
- Trend estimates can be verified with model-based estimates.
- Other soil properties can also be determined from the samples collected.

#### *Disadvantages*

- Laborious and expensive to conduct.
- Large uncertainties because of high spatial variation of soil carbon.
- Sample size needed for monitoring purposes difficult to determine without earlier information on variation of soil carbon.
- Feasible sampling interval is relatively long (e.g. ten years).
- Annual emissions/removals can only be estimated by interpolation.
- Uncertainty associated with the annual estimates, obtained by interpolation, is relatively high, especially when disturbances, such as fires or logging leading to deforestation and forest degradation, change from year to year.
- Future scenarios difficult to develop.
- QC/QA activities difficult to implement.

#### *Model-based method*

##### *Advantages*

- Improve estimates of changes in carbon stocks in soil and estimates of emissions/removals associated with these changes in line with IPCC GPG LULUCF and UNFCCC reporting requirements compared with the default method.
- Improve scientific understanding of carbon dynamics in soils.
- Can provide time-series annual estimates without interpolation.
- Makes use of measurements taken elsewhere.
- An increasing amount of measurements and further development continuously improve the system.
- Application in one country benefits from all previous developments of the system in other countries.
- Results of validity tests in one country may be relevant for other countries.
- Gives the possibility of improving the model using measurements.
- Can be used for estimating soil carbon pool in the past, present and future if input data are available.
- Can be used to estimate scenarios.
- Links elementally to forest inventory, changes in forest inventory data reflected in the results of soil carbon monitoring.
- Lower costs compared with soil survey.

##### *Disadvantages*

- Determination of the initial carbon stock may be difficult; problem with the steady state assumption, input data from the past may not be available.
- Soil carbon cycle may be inadequately described in the model: effects of factors that have an effect on soil carbon but not included in the model.
- Reliable uncertainty estimates may be difficult or impossible to obtain.

- All input data needed may not be available locally, necessary to complement using information from elsewhere.
- Potential bias of the model difficult to estimate.





## 5. Soil carbon monitoring in the United Republic of Tanzania

### SOIL ORGANIC CARBON STOCK INVENTORY IN THE UNITED REPUBLIC OF TANZANIA

#### Background and rationale

Among other non-industrialized (non-Annex I) countries of the UNFCCC, the United Republic of Tanzania had very limited and spatially unrepresentative information on soil carbon and former data did not enable estimation of the soil organic carbon stock on a country or regional scale. In this report, the United Republic of Tanzania represents a tropical non-Annex I country, where a nationwide soil survey needed to be designed in order to provide information necessary for national purposes, as well as for reporting under the UNFCCC.

The objective of the first soil inventory is to obtain unbiased estimates for the mean and the between-site variation of the soil organic carbon stock in the United Republic of Tanzania. These estimates will be determined for three land-use categories: forest land (including natural and planted forests), cropland and grassland.

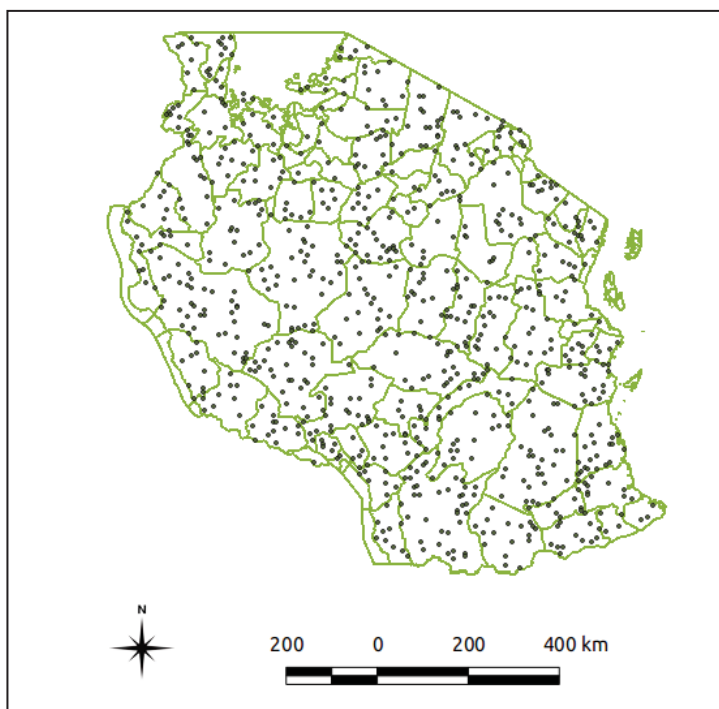
Soil organic matter is influenced by a number of factors, mainly climate (temperature and rainfall), vegetation types, soil types and human activities. The influence of climate and natural vegetation on the levels of soil organic matter is recognized over broad geographic areas. Generally, in similar moisture conditions and comparable soils and vegetation, the soil organic matter is higher in cooler climates than in warmer ones. Moreover, high rainfall promotes vegetation growth and hence production and accumulation of soil organic matter. Since plants (particularly natural vegetation) are the major source of soil organic matter, vegetation types and their density influence the soil organic carbon stock. Soil drainage and texture influence soil organic matter and hence soil organic carbon within local landscapes. Generally, fine-textured soils are known to have a higher soil organic matter content than sandy soils. This is mainly because the organic residues returned to fine-textured soils are generally higher than in coarse-textured soils as a result of their greater nutrient- and water-holding capacities, which promote greater plant production. In addition, the formation of clay-humus complexes in fine-textured soils minimizes soil organic matter degradation. Other factors that influence soil organic carbon content include human activities such as cropping and tillage systems and soil management practices. These factors should therefore be considered when planning a cost-effective long-term soil sampling scheme for a soil carbon monitoring system in the United Republic of Tanzania.

### NAFORMA sampling design

In the United Republic of Tanzania, National Forestry Resources Monitoring and Assessment (NAFORMA) was designed in 2010, since the state and trends of forestry resources were largely unknown and available information was fragmented and outdated (Tomppo *et al.*, 2010; NAFORMA, 2010). NAFORMA utilizes stratified sampling design. In the first phase, a dense grid of clusters, at 5 x 5 km spacing, was made over the United Republic of Tanzania. From this grid the optimal sampling ratio (Phase II) was calculated for each stratum considering the following variables: wood volume estimates based on satellite images calibrated with field data from past inventories, measurement time and slope. In this stratification, information on soil properties (e.g. FAO World Reference Base for Soil Resources or the Harmonized World Soil Database [FAO and the International Institute for Applied Systems Analysis – IIASA]) was not used, since the major target was assessment of the growing stock. In addition, global soil databases focus more on morphological characteristics of the soil than on soil carbon quantity and dynamics. To come up with the final NAFORMA sampling design, the variations in number of plots, crew days and coefficients of variation of area and volume at different costs for the United Republic of Tanzania were tested. Eventually the model with 3 419 clusters and 32 551 plots to be measured in 6 259 days was adopted (estimated costs were USD2.5 million). The distribution of NAFORMA clusters countrywide is shown in Figure 6.

FIGURE 6

Location of the permanent sampling clusters of NAFORMA where soil samples are taken



The NAFORMA cluster is an inverted L-shaped arrangement of plots. The distance between clusters varies by stratum, from 10 to 45 km. A normal cluster in a flat terrain has ten plots, five on each leg. Clusters in difficult terrain in terms of accessibility and prohibitive slopes have six or eight plots. Forested areas have more clusters than non-forested areas. The original 5 x 5 km grid has therefore been thinned, based on the probability of favouring denser plots in areas with higher wood volume. The distance between plots in a cluster is 250 m. The actual total number of clusters equals 3 419, and the total number of plots equals 32 660. A quarter of the clusters (854) are permanent; the permanent clusters were also used in the soil survey.

The results of the first inventory form the basis for estimating changes in the soil organic carbon stock over time. These results will be needed independently of the method to be used to estimate temporal soil carbon changes. If these changes are to be estimated using repeated measurements of the soils after some years, the results of the first inventory provide reference data for the initial organic carbon stock of the soils as well as information necessary to design an effective and adequate sampling for the second inventory. If the changes over time are estimated using a model-based approach, such as that based on the Yasso07 soil carbon model, the results of the first inventory can be used to test the validity of the model-based soil carbon stock estimates or calibrate the model-based method to reproduce the measured soil carbon stock values.

### Sampling design in first soil survey

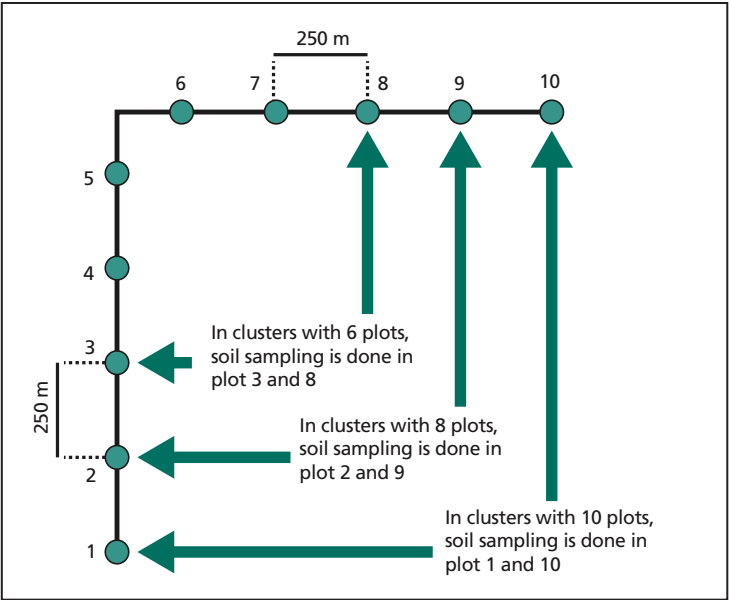
The soil sampling design consists of decisions at five hierarchic levels, namely:

- cluster selection for sampling
- sample plot selection within the clusters
- selection of sample point locations inside the sample plots
- selection of soil sample collection method and decision on sampling depth
- decisions on soil sample composition technique.

In the case of the Tanzanian soil survey, a grid of sampling clusters was designed as part of the planning process of the NAFORMA stratified sampling design (Tomppo *et al.*, 2010) and the soil survey used a subsample of the plots from permanent NAFORMA clusters (Figure 7). Soil samples were taken from each permanent cluster ( $n > 800$ ).

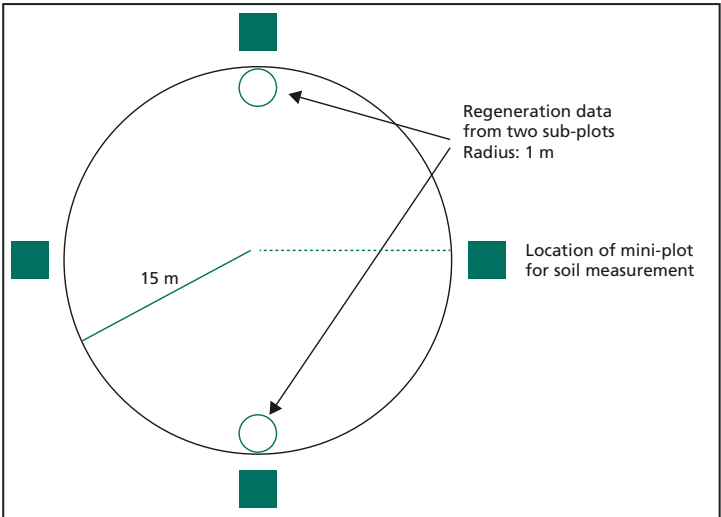
Systematic sampling of plots from each cluster is employed, since a priori information on the soil carbon changes in the sampled population is not available. The sampling gives the possibility of assessing the relationship between soil variables and stand variables as well as monitoring the effects of land-use changes on soil organic carbon by site. In practice, on each permanent cluster, two plots located at the extreme ends of the cluster were selected for soil sampling (Figure 7). Therefore, in a ten-plot cluster soil samples will be taken from plots one and ten, and in an eight-plot cluster they are taken from plots two and nine. In a six-plot cluster soil samples will be taken from plots three and eight.

FIGURE 7  
Selection of plots for soil sampling from a permanent NAFORMA cluster



The NAFORMA plot consists of concentric circles of 1-, 5-, 10- and 15-m radii in which trees are measured depending upon their size. Soil samples are taken just outside the 15-m radius of the plots. At each soil sampling plot, four soil mini-pits are excavated and samples taken. The sampling points should be located at the main compass points east, south, west and north (Figure 8). In each pit, three samples are taken at soil depths of 1–10, 10–20 and 20–30 cm. Samples from the four pits are combined according to the three depth levels and put into one plastic bag to form a composite soil sample of the site.

FIGURE 8  
Four soil sampling mini-pits are located on the circle of the inventory plot at the main compass points (east, south, west and north)



### Soil sampling

On mineral soils, soil sampling will cover the organic soil layer on top of the mineral soil, if an organic layer exists, plus the topmost 0–30 cm mineral soil layer at each sample point. On organic soils, similar sampling protocol according to the topmost 0–30 cm layers will be applied (definitions of organic and mineral soils are given in Annex 3A.5 in IPCC, 2006). A soil mini-pit will be dug at each sampling location to collect soil samples (see Figure 9). One wall of the pit will be prepared for soil sampling. A volumetric soil sample (e.g. 150 ml, a cylinder with a diameter of 6 cm and height of 5.3 cm) will be taken from the middle of each 10-cm deep mineral soil layer (0–10, 10–20 and 20–30 cm). Where the soil is too hard to dig a pit 30-cm deep, sampling will be limited to the upper 10 or 20 cm layers, and this will be noted in field forms.

In the field, the soil samples from each layer should be removed from the sampling cylinders (see Figure 9) and put into plastic bags with all necessary identification information (sampling time, person in charge, cluster, plot, soil layer) on the cover (and nothing else). Soil sampling and any deviations from the sampling design should be described on the field form. Soil samples should be air-dried as soon as feasible. Air-drying can be done in normal room temperatures or in the sun to prevent soil samples from harmful microbiological activity before proper drying in a constant temperature of 40° C (oven drying).

If an organic layer exists, a sample of this layer is taken next to the soil pit on its northern side. The sample should be taken as near to the pit as possible, but from locations that have not been disturbed when digging the soil pit. It is taken by cutting a 20 x 20 cm piece of the entire thickness of the organic layer. The sample should be cleaned carefully from the remains of mineral soil, because contamination of mineral soil will add measurement error to the carbon analyses that follow.

This volume-specific sampling method is preferred over sampling a slice of soil covering the entire 0–30 cm soil layer for two important reasons. First, it is not possible to determine the volume weight of soil based on the slice, and this information is needed to calculate the stock of soil organic carbon (kg C/ha and kg C/m<sup>3</sup>). Second, sampling a slice of soil can easily result in a considerable measurement error because soil carbon content varies with depth and it will be difficult to obtain a slice where each soil layer is equally represented.

FIGURE 9A

The locations (in 0–10, 10–20 and 20–30 cm soil layers) of the volumetric samples are marked on the wall of the soil pit



FIGURE 9B

The sampling cylinder is pushed into the wall with a plastic hammer. When hammering, it helps to cover the cylinder with a wooden plank



FIGURE 9C

The core with soil sample is extracted carefully from the wall of the pit, using a trowel or a knife if necessary



FIGURE 9E

Where soil is dry and too loose (*top*) to obtain a volumetric soil sample, it is more practical to take soil samples by pressing the cylinder in at the top (*bottom*)



FIGURE 9D

Using a sharp field knife, any excess soil over the core should be removed to ensure a volumetric soil sample



Photos by S. Dalsgaard



### Observations at a sample point

The volume of stones is estimated visually from the wall of each soil pit by recording the coverage of stones in 10 percent classes (proportion of stones <10, 11–20, 21–30 percent ...). The estimated stone volume is used in the calculations of the total carbon stock of the assessed soil layers (i.e. stone volume excluded, since there is no organic carbon in stones).

While in the field, the soil samples from the vertical side of the soil pits are also used to determine soil colour and estimate soil texture and structure. These properties are ascertained at the middle of 0–10, 10–20 and 20–30 cm depths. The protocol for estimation is included in the field manual (NAFORMA, 2010), Annex 3a, 3b and 3c. To save time in the field, soil colour and texture can be determined in the laboratory.

### Compositing soil samples

All soil samples that represent the same soil layer are composited by a plot to reduce the costs of laboratory analyses. These composite samples should always comprise the same number of subsamples. Samples taken from different soil layers are kept separate as well as samples taken from different plots.

Plot-level samples are needed to be able to estimate variability between plots and to allow monitoring of soil carbon changes with a repeated inventory according to land-use category. Information on variability is necessary to calculate statistical confidence estimates for the soil organic carbon estimates obtained. Furthermore, these are used in the planning of an effective and adequate sampling for a repeated inventory in the future. Plot-level soil carbon estimates are also necessary in order to relate the results of soil carbon stocks and possible future soil carbon changes to the present and changed stand and tree characteristics. Sampling the same sites again as part of the possible repeated inventory is also cost efficient, because the resulting estimate of the change in soil carbon will be more reliable.

### Feasibility of the soil sampling design and its practical implementation

The soil sampling design was planned for a soil survey and, as such, it is not necessarily feasible for soil carbon monitoring purposes. Planning an appropriate soil sampling scheme for soil organic carbon monitoring is a big challenge. According to Rossi *et al.* (2009), measurements of soil organic carbon are normally restricted by the ability to produce rapid, cost-effective and precise sampling schemes. In order to design an effective sampling strategy (including stratification according to relevant variables that reflect rate of change) for soil carbon monitoring, additional data on spatial and temporal variation of the soil organic carbon are needed. In a study conducted in five common forest types in the southeastern United Republic of Tanzania, Rossi *et al.* (2009) concluded that the optimal sampling scheme varies greatly with vegetation type as a result of the different spatial behaviour of soil organic carbon in forests and depends on the required precision and research question. Hence, as discussed in Chapter 2, under Information needed to design a repeated soil carbon inventory, these factors

should be taken into consideration when designing soil sampling strategies for monitoring soil organic carbon in tropical and subtropical regions, including the United Republic of Tanzania.

Continuous changes in land use and its effect on soil organic carbon is another challenge for soil carbon monitoring in the United Republic of Tanzania. For example, declines in soil organic matter as a result of converting forest land or natural vegetation to agricultural land have been reported in chromic luvisols in the semi-arid areas of the northern United Republic of Tanzania. These declines varied with initial vegetation type and were more rapid in coarse-textured rather than in fine-textured soils (Solomon, Lehmann and Zech, 2000). This implies that periodic measurements of soil organic carbon at the same location under the same land-use type for long periods will produce data that change consistently over time. Soil sampling in the NAFORMA permanent clusters (Figure 6) for soil organic carbon monitoring is currently the most practical and cost-effective strategy for the United Republic of Tanzania since these clusters cover the whole country and are also being sampled by NAFORMA for other related parameters that can explain soil organic carbon changes over time. The challenge here is that the sampling density in NAFORMA clusters is generally uniform throughout the country irrespective of vegetation or land-use type. It has been found by Rossi *et al.* (2009) that the optimal sampling distance for measuring mean soil organic carbon stocks varies with vegetation type and hence with land-use type. To be cost effective, sampling density should be lower in extensive areas with similar land cover or vegetation types than in areas with different vegetation types.

Because of practical limitations, only four subsamples per plot were collected from layers 0–10, 10–20 and 20–30 cm. However, effective soil monitoring, i.e. observing possible changes, may need ten to 30 subsamples per plot (from each soil layer) (e.g. Tamminen, 2003; Tamminen and Derome, 2005) and sampling for monitoring purposes will be more laborious. In the first soil survey conducted, soil samples were collected from the middle of layers 0–10, 10–20 and 20–30 cm, and the topmost 0–10 cm layer was not sampled totally. Since soil organic carbon content in the topmost 2 cm may be higher than in the 2–8 cm layer where the sample was taken, this sampling may slightly underestimate soil carbon stock, but it is less sensitive to between-team variation in the sampling technique (how carefully the litter layer is removed).

Soil sampling design, sampling practices in the field and efficacy of laboratory analyses were evaluated in March 2012; they appeared to have followed the instructions given and produced reliable soil survey data for the estimation of soil carbon stock in the United Republic of Tanzania.



## MEASUREMENTS NEEDED FOR DESIGNING A REPEATED SOIL CARBON SURVEY IN THE UNITED REPUBLIC OF TANZANIA

### Number of soil sampling plots to be measured

In the United Republic of Tanzania, the regionally representative mean soil carbon stock and its standard deviation are measured by NAFORMA and results will be available in the near future. This information, together with the estimate of soil carbon change, is used for the assessment of the number of sample plots needed for evaluation of changes with repeated measurements (see Chapter 2 for more details). A first estimate of the rate of soil carbon change according to land-use or vegetation cover classes can be derived with the help of soil modelling. The potential interval of soil carbon measurements may be a decade or a minimum of five years, but an appropriate interval can be determined when a priori information on between-site variation of soil carbon stock and an estimate of the rate of change are available (see Chapter 2).

### Within-site variation and determination of number of subsamples per plot

Knowledge on within-site variation in the soil carbon stock is used to determine the number of subsamples per plot yielding estimates that are accurate and precise enough for monitoring purposes. In general, 20–30 subsamples per plot are considered to be an appropriate sample size (Tamminen, 2003; Tamminen and Derome, 2005; Rossi *et al.*, 2009; Muukkonen, Häkkinen and Mäkipää, 2009) but, in practice, a much smaller number of subsamples is currently used (e.g. Munishi and Shear, 2004). In the United Republic of Tanzania, a study on spatial within-site variation of soil carbon stock in different soil layers and in different soil types needs to be conducted before the second round of a soil inventory. Results obtained will improve the efficiency of consecutive inventories in the United Republic of Tanzania and in other countries with similar soil types and climatic conditions.

## MODEL-BASED METHOD

### Overview of the task

Practical application of a model-based soil carbon monitoring system in the United Republic of Tanzania is explained in this section, according to the steps described in Chapter 3, under Practical application of a model-based soil carbon monitoring system.

In the United Republic of Tanzania, the model-based soil carbon monitoring system needs to be employed, which relies on more limited input data than in countries having longer traditions of forest and soil inventories. In the United Republic of Tanzania, there is less input information available, the existing information may be less detailed or less reliable and information on the past is probably extremely limited. It is worth noting, however, that the availability

of input information is currently improving greatly as a result of the first NAFORMA and soil carbon inventories conducted in the country.

The above evaluation of the situation follows from a NAFORMA description ([mnrt.go.tz](http://mnrt.go.tz) > Programmes and projects), which reads: “In Tanzania, the state and trends of forestry resources are largely unknown and the existing information is fragmented and outdated”. “National Forestry Resources Monitoring and Assessment (NAFORMA) of Tanzania is a multistakeholder project aimed at capturing accurate and timely information regarding the state and extent of the forest and trees outside forest (TOF) resources of Tanzania. This is done through mapping the current and historical extent of the forest and TOF resources and by establishing a system of permanent sample sites throughout the country. Combined, these will allow for future monitoring of the development of the forest resources through continual re-measurements. NAFORMA was launched in May 2009.”

The ongoing inventories of forest resources and soil carbon will provide valuable information to establish and apply a model-based soil carbon monitoring system in the United Republic of Tanzania. It will then be possible to estimate current pools of soil carbon and thus start evaluating the reliability of the model-based soil carbon monitoring system in the country. As soon as the forest inventory is repeated in the future, the model-based soil carbon monitoring system can be used to estimate changes in the soil carbon pools compared with the present situation.

The model-based soil carbon monitoring system could also be used for scenarios of soil carbon development based on those of forest resource development if such forest scenarios were available. These scenarios could be used to study the effects of alternative trends in forest resources on soil carbon pools and to support the design of possible future soil carbon inventories using similar methods to those applied in northern forests (Peltoniemi *et al.*, 2007).

The basic source of biomass and litter production information for the model-based soil carbon monitoring system is NAFORMA forest inventory data. Thus, the model-based soil carbon monitoring system is elementally linked to the NAFORMA forest inventory. However, before being used in soil carbon modelling, the NAFORMA data must be complemented by information on biomass conversion and biomass turnover to estimate litter production. Some local information may be available on these complementing factors but it may also be necessary to use data from other countries and international literature.

Climate data needed for model-based soil carbon monitoring may be obtained from local sources or global databases, such as the IPCC Data Distribution Centre.

### Soil carbon model choice

After forming an overall picture of the task (see previous section), the next step in applying a model-based soil carbon monitoring system in the United Republic of Tanzania is the selection of the soil carbon model to be used. There are certain requirements for the soil carbon model that may be used as selection criteria.

These requirements and the selection criteria can be grouped into four categories.

1. Relevancy. The soil carbon model needs to account for the most important factors affecting soil carbon pools and changes in soil carbon pools in the United Republic of Tanzania when it is used as a component of the model-based soil carbon monitoring system. These factors are basically i) climate; ii) litter input quantity and quality; iii) natural disturbances; iv) ecosystem management; and v) land-use change.
2. Practicability. It must be feasible to apply the soil carbon model in practice. This means that i) input information to the model is available; ii) it is possible to link the model calculations to NAFORMA information; and iii) the soil carbon model is suitable for establishing a practicable model-based soil carbon monitoring system.
3. Reliability. The soil carbon model needs to give reliable results in the soil carbon pool, change in the soil carbon pool, decomposition rate of litter and soil organic carbon, and heterotrophic soil respiration.
4. REDD+-readiness. The soil carbon model and the results produced need to meet the criteria set for carbon accounting systems under the REDD+ mechanism.

It is probably most practicable to select the soil carbon model to be used from the existing established soil carbon models such as CENTURY (Parton *et al.*, 1987); RothC (Coleman and Jenkinson, 1996); ROMUL (Chertov *et al.*, 2001); SCUAF (Young *et al.*, 1998) and Yasso07 (Tuomi *et al.*, 2009; 2011). Many current soil carbon models meet the selection criteria and could thus be used. However, if a complicated model with a lot of input data requirements is selected, all these data may not be available across the United Republic of Tanzania and it may be necessary to run the model using some default values. Some models may also be more suitable for a statistically sound uncertainty analysis of the results.

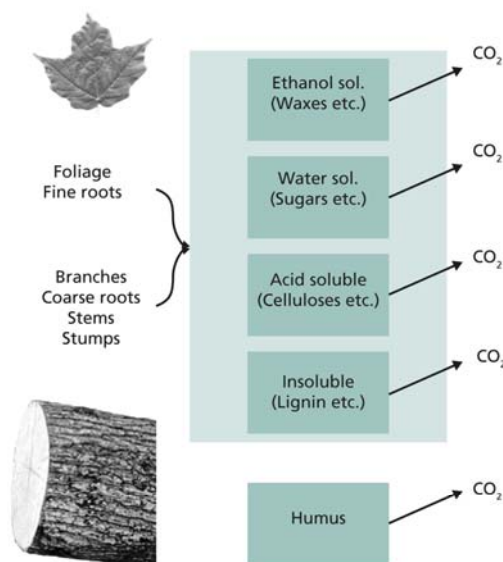
Yasso07 is one of the soil carbon models meeting the selection criteria (Figures 10, 11). The advantages of this model are i) that it requires limited and generally available input data; ii) the results of the model are accompanied by statistically meaningful uncertainty estimates; iii) it has been developed using large worldwide data sets also including measurements in the tropics; and iv) it has already been used for UNFCCC reporting in industrialized countries.

Information on uncertainty will improve the completeness of soil carbon estimates in line with UNFCCC decision 17/CP.8 stating that “non-Annex I Parties to the UNFCCC are encouraged to provide information on uncertainty associated with GHG inventory data, and to describe the methodologies used, if any, for estimating these uncertainties”.

Whatever soil carbon model is selected it must give reliable results on soil carbon stocks, changes in soil carbon stocks and soil carbon dioxide emissions as well as the effects of the factors affecting these features.

The remaining sections describing the application of a model-based soil carbon monitoring system in the United Republic of Tanzania are based on Yasso07, since this was selected as the soil carbon model to be used. Nevertheless, most of the information also applies to the use of any other soil carbon model.

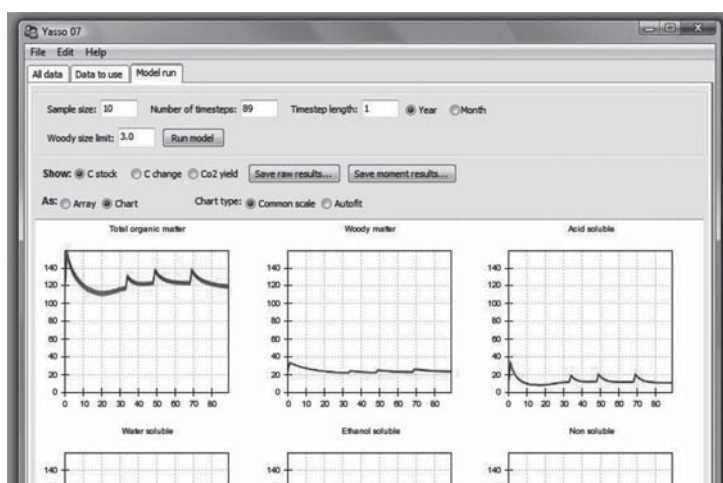
FIGURE 10  
Flow chart of the Yasso07 litter and soil carbon model



Source: Tuomi *et al.*, 2008; 2009; 2011; Thum *et al.*, 2011

Note: The boxes represent fractions of soil organic carbon, the arrows carbon fluxes. For input information, the Yasso07 model uses data on the quantity and quality of carbon input to soil and basic climate data. Output of the model consists of estimates for the stock of soil organic carbon, changes in the soil carbon stock and soil carbon dioxide emissions resulting from heterotrophic respiration.

FIGURE 11  
The Yasso07 litter and soil carbon model can be run on a user interface



Source: Tuomi *et al.*, 2011

Note: This is available for Windows, Macintosh and Linux computer environments. It is useful both for learning the model and for limited studies. The computer code of the model is also available, which is more useful for extensive studies. The user interface, code and information are available at [www.environment.fi/syke/yasso/](http://www.environment.fi/syke/yasso/)

### Reliability of model-calculated soil carbon estimates

The suitability of different soil carbon models for the model-based soil carbon monitoring system in the United Republic of Tanzania was discussed in the previous section. An essential prerequisite for the actual usefulness of any soil carbon model in this context is the reliability of the results of the model when linked to the entire monitoring system.

The reliability of the soil carbon results can be tested by comparing model-calculated estimates with measurements taken in the United Republic of Tanzania or under comparable conditions elsewhere. Relevant variables to compare are the soil carbon pool, soil carbon changes and decomposition rate of litter and soil organic matter.

Comparisons with data on the soil carbon pool can be carried out at site or regional scale. The soil carbon inventory carried out as part of NAFORMA will produce regional estimates of the soil carbon pool, which can be compared with similar estimates calculated using the model-based soil carbon monitoring system. These kinds of comparisons can also be conducted at a site scale if such data on the soil carbon pool are available. Similar comparisons can be carried out in terms of soil carbon pool changes if data are available.

Comparisons with data on litter decomposition can be conducted using measurements already taken elsewhere under similar climate conditions or in experiments established specifically for this purpose in the United Republic of Tanzania. For example, Yasso07 databases already contain litter decomposition measurements from the tropics in Central America (Tuomi *et al.*, 2009) and recent studies have been carried out in Benin in Africa (Guendehou *et al.*, submitted manuscript). Other soil carbon models have also been used in investigations in the tropics. Measurements on litter decomposition in the major land cover types in the United Republic of Tanzania would be highly useful.

If these comparisons reveal that the model-calculated estimates deviate significantly from the measurements in any way, then the model-based calculation system needs to be improved. It may be possible to recalibrate the soil carbon model using the new measurements. If this recalibration does not correct the error, it will be necessary to find a reason for the deviation in the structure of the model and modify it in order to solve the problem. This kind of continuous evaluation and improvement has already been a fundamental part of the development of the Yasso07 soil carbon model and similar studies are currently under way.

Reliability control of the soil carbon model is an important step in applying the model-based soil carbon monitoring system in the United Republic of Tanzania. It will be necessary to test the model adequately against measured data to evaluate the reliability and dependability of model-calculated results correctly.

### Spatial calculation units

There are a few issues to be accounted for when deciding upon the geographic calculation units to be applied in model-based soil carbon monitoring in the United Republic of Tanzania, namely i) the availability of input data for these units; ii) homogeneity of conditions inside the units with respect to the soil carbon

cycle; and iii) practical issues, such as the technical feasibility of the calculations and the spatial detail needed in the use of results. It is worth noting that the spatial calculation units may be non-uniform regions or uniform pixels.

Of the types of input information, climate data are probably the most flexible regarding the calculation units. Climate data can be obtained on a grid and it is possible to interpolate this information for more detailed resolutions or summarize it for coarser resolutions. It may also be possible to derive information on litter input information separately for each NAFORMA forest inventory site. However, it is still not certain whether it is feasible to carry out calculations at this level of detail by inventory site because it may not be possible to calculate estimates for the initial soil carbon pool separately for each inventory site (see section on Initial soil carbon stock). The method of accounting for land-use change may set its own restrictions on the choice of spatial resolution of soil carbon calculations.

Climate conditions need to be adequately homogenous inside the spatial calculation units, because climate is an essential factor affecting the soil carbon cycle. This is especially relevant if relatively large regions are chosen for the calculation units. The calculations of litter input may be at a more detailed spatial resolution, since it is possible to pool the litter input values over a larger region and use these pooled values in actual soil carbon calculations.

### **Litter input and litter quality estimates**

NAFORMA forest inventory data are the primary source of information to estimate litter input to soil in each spatial calculation unit. The use of these data forms a major link between the model-based soil carbon monitoring system and the NAFORMA forest inventory. In some areas in the United Republic of Tanzania, vegetation other than trees contributes significantly to litter production. In these areas, it is also important to account for this vegetation in order to estimate the total litter production correctly.

Among other things, the NAFORMA forest inventory produces estimates of forest resources in terms of timber volume, as forest inventories usually do. To derive estimates of litter production from these estimates of timber volume, the latter are usually converted to biomass estimates by tree biomass component (foliage, branches, stem, coarse roots and fine roots) using biomass expansion factors. Litter production estimates are then calculated from the biomass estimates by multiplying them by biomass-component-specific biomass turnover rates.

Timber volume -> (biomass expansion factors) -> biomass by biomass component (foliage, branches, stem, coarse roots and fine roots) -> (biomass turnover rates) -> litter input to soil from each biomass component.

The estimates of litter production are needed separately for each biomass component because litter of these components decomposes at different rates in soil.

Information needed for this derivation of litter production estimates from timber volume estimates may probably be obtained to some extent from specific ecosystem studies in the United Republic of Tanzania. Additional biomass and

litter studies are suggested as one type of local measurement that would support the application of the model-based soil carbon monitoring system. Nevertheless, it seems necessary to complement the Tanzanian biomass and litter production information with similar information available elsewhere under comparable conditions.

Carbon is also brought to soil in the form of residues of ecosystem management operations (e.g. forest harvesting) and as a result of natural disturbances. These components of the soil carbon input must be estimated and included in the model-based soil carbon monitoring system. It is also important to estimate any existing litter production of vegetation other than trees.

In addition to the quantity of litter input to the soil, soil carbon models require information on the quality of the litter. This may be obtained from local sources to some extent but it may be necessary to complement the information using databases related to the soil carbon model to be used.

### Climate data

Climate data requirements vary from one soil carbon model to another. However, each model uses information on temperature and precipitation in some form, because temperature and moisture are the main climate variables affecting carbon cycling in soil. It appears that the climate data needed for each model is available for the United Republic of Tanzania, either from local sources or from global databases, such as those available at the IPCC Data Distribution Centre.

As discussed above (section on Spatial calculation units), it may be necessary to fit the spatial resolution of the climate data to that of the spatial calculation units. This is quite a straightforward operation if the primary climate data are at quite a dense resolution. A change in the resolution by interpolating does not thus cause any significant error.

### Land-use change estimates

The method of taking into account the effects of land-use change in soil carbon calculations depends on the spatial resolution of the land-use information and the spatial calculation units used. If the calculations are carried out separately for different land-use classes, land-use change means transfer of soil carbon from one land-use category to another. If the calculations are carried out for entire regions and the results summed over various land-use categories, land-use change is accounted for by changing the quantity and quality of carbon input to soil (as a result of changes in vegetation, ecosystem management and natural disturbances).

### Initial soil carbon stock

Simulations of soil carbon using a dynamic model are usually started from steady-state conditions. This means that it is assumed that the input of carbon to soil equals the output of carbon from soil and, consequently, the carbon pool of soil does not change over time. The steady-state assumption is commonly used because it is the only practical way to start calculations and come up with a division of the



total soil organic carbon between the pools of a soil carbon model. The suitability of this approach and assumption needs to be considered carefully in the United Republic of Tanzania and possible consequences carefully evaluated. Uncertainty about the initial soil carbon pool can be accounted for in the overall uncertainty analysis of the model-based soil carbon monitoring system.

The initial steady-state soil carbon pool needs to be calculated separately for each spatial calculation unit. There are two alternative methods of calculating these initial pools: i) by assuming steady state with litter input at the beginning of the calculation; or ii) making the model-calculated soil carbon pools similar to those measured in the soil carbon inventory by adjusting litter input to soil as needed.

Estimating these initial steady-state pools and comparing them with measured soil carbon pool values provide information on the consistency of the model-based soil carbon monitoring method compared with measurements. If the first method above is used and the calculated pools deviate significantly from the measured pools, this indicates that either i) litter input and soil carbon cycle are calculated correctly but the soil carbon pool is not in a steady state; ii) litter input or soil carbon cycle or both are calculated incorrectly but soil is still in a steady state; or iii) same as ii) but soil is not in a steady state. A possible issue related to the second method above is that if it is necessary to change the litter input values to come up with the inventoried soil carbon pool values it would be difficult to know which litter input values to use in the actual soil carbon simulations. It would be inconsistent to use the adjusted values to calculate the steady state and continue using non-adjusted values for the rest of the calculation period.

### **Simulation of soil carbon changes**

The final step in applying the model-based soil carbon monitoring system is the actual simulation of the cycling of soil carbon. In this simulation, the initial soil carbon pools determined for each spatial calculation unit are used as starting-points. Time series of the driving variables (litter input, climate, land-use change, natural disturbances and ecosystem management) are used as input to the soil carbon model, and the model calculates the development of the soil carbon pool.

## **LOCAL MEASUREMENTS TO SUPPORT THE MODEL APPLICATION**

### **Purpose of local measurements**

Local measurements, in addition to NAFORMA forest inventory data, can support the application of the model-based soil carbon monitoring system in the United Republic of Tanzania in various ways. These measurements can be used i) as input data to the calculations; ii) for testing the validity of the system, i.e. the reliability of the results obtained; and iii) for improving the soil carbon model by recalibrating or restructuring it where necessary.

Particularly useful local measurements include data on the soil carbon pool, decomposition rate and chemical quality of litter and litter production.



### Soil carbon pool

The size of the soil carbon pool is a principal variable of the model-based soil carbon monitoring system. Many changes in the pool are calculated in proportion to its size. It is thus essential that the model-calculated estimates for the size of the soil carbon pool are reliable.

The soil carbon inventory conducted as part of NAFORMA data collection produces valuable information on the carbon pool of soil in the United Republic of Tanzania. These data can be used to test the validity of the model-based soil carbon monitoring system, improve it if needed and determine the initial soil carbon pools to be used as starting values of model-based soil carbon calculations.

Other local soil carbon measurements are also useful, where available. However, these may be taken for different purposes, particularly for soil fertility studies. The main difference that may make data from these measurements not comparable is that the sampling protocol employed may not be as representative across the entire country as the one used for the soil carbon inventory conducted by NAFORMA.

### Litter decomposition and litter chemistry

Litter decomposition is an important process affecting changes in the soil carbon pool and heterotrophic soil respiration, especially at relatively short time scales of months or years. For this reason, in order to obtain correct estimates of soil carbon changes at these time scales, litter decomposition estimates must be reliable.

Litter chemical quality is used as an input variable of the Yasso07 model, and it is taken into account by dividing the litter into four chemical fractions.

Local measurements of litter decomposition and litter chemical quality thus provide valuable information supporting the model-based soil carbon monitoring system in the United Republic of Tanzania. An efficient way to collect this information is to conduct harmonized litter decomposition experiments. These experiments should aim at covering the range of variability in the decomposition rate and the chemical composition of common tree species across the United Republic of Tanzania.

A practical way of measuring the litter decomposition rate is to use the litter bag method (e.g. [andrewsforest.oregonstate.edu/research/intersite/lidet.htm/](http://andrewsforest.oregonstate.edu/research/intersite/lidet.htm/)). In this method, litter is left to decompose in mesh bags in the field for varying periods (months to a year in the tropics) and mass loss and chemical quality of the litter are followed by sampling the litter bags at certain intervals.

In practice, it would be useful to select litter of some of the most common tree species for a litter decomposition experiment. The sites of the experiments should, if possible, cover the main ranges across the United Republic of Tanzania of variability in temperature and precipitation, which are the main climate factors affecting litter decomposition. Such an experiment would provide valuable and useful information for testing the validity of litter decomposition estimates calculated using the Yasso07 soil carbon model. The data obtained could also be used to recalibrate the model for use in the country if necessary.

This kind of an experiment has already been conducted in Benin to support a national Yasso07 application. The experiment there resulted in valuable experience on conducting litter bag experiments and using the data to improve the Yasso07 model.

### Litter production

Estimates of litter production provide essential input information for the model-based soil carbon monitoring system in the United Republic of Tanzania. These estimates are as crucial to soil carbon estimates as the soil carbon modelling itself, because model-calculated soil carbon estimates are affected directly by litter production estimates. For this reason, local measurements of litter production would provide crucial support.

## RECOMMENDATIONS FOR SOIL CARBON MONITORING IN THE UNITED REPUBLIC OF TANZANIA

There are various aspects to consider when planning future actions of soil carbon monitoring in the United Republic of Tanzania. Relevant aspects include at least: i) acknowledgement of the growing need for soil carbon monitoring information; ii) ongoing and planned work and processes; iii) estimated cost efficiency; and iv) no-regret principle. With regard to these factors, the following are rational steps to be taken.

1. *Conduct the first soil carbon survey using resources available and the guidelines given in this report.* This survey will result in estimates for the carbon stock of soil and geographic distribution of the stock across the United Republic of Tanzania, based on actual samples from all permanent sampling clusters. These estimates are important as reference for any future soil carbon monitoring activities. Based on the variability observed during the first soil carbon survey, a cost-efficient soil sampling scheme will be proposed for a long-term soil carbon monitoring system. The soil samples obtained during the first survey include soil organic carbon, soil pH, bulk density, soil texture and soil colour. In forthcoming inventories, soil properties that do not normally change within a short period, such as soil texture, need not be determined, hence reducing the costs of analyses.
2. *Link a soil carbon simulation model to the NAFORMA forest inventory system and use this system to simulate scenarios of soil carbon development.* This can be done at relatively low cost and the system will support any method used to monitor soil carbon. If the survey-based method is applied, estimates of soil carbon changes can be used to design an effective sampling scheme for the second (repeated) soil carbon survey. If the model-based method is applied, this step actually means establishment of the method. In other words, since the United Republic of Tanzania is aiming at soil carbon monitoring, this would be a useful step in any case. The model needs to be tested and verified, and applicability in the NAFORMA context confirmed (see above section on Reliability of model-calculated soil carbon estimates)

before application in reporting soil organic carbon stock and carbon stock change estimates under UNFCCC is possible.

3. *Take actions to improve the reliability of the model-based system, if this system is to play a role in soil carbon monitoring.* The following steps support the development of the model-based method in particular. They can also be seen to support the survey-based method if the simulation of soil carbon changes is considered practicable to improve the efficiency of the second soil carbon survey. Experiments on litter decomposition rate should be carried out. This is important in order to relate the decomposition rate of different litter types to the rate at which organic matter is returned to the soils. The validity of soil carbon modelling should be tested by comparing results with the first soil carbon survey and local measurements of litter decomposition rate. If necessary, the model should be improved according to the validity tests.

These steps will enable progress in soil carbon monitoring to be made, using either the repeated soil carbon survey or the model-based approach.



# References

- Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B. & Kimetu, J. 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. *Agricultural Systems*, 94: 13–25.
- Batjes, N.H. (ed.) 1995. *A homogenized soil data file for global environmental research: a subset of FAO, ISRIC and NRCS profiles (version 1.0)*. Wageningen, International Soil Reference and Information Centre (ISRIC).
- Cao, M. & Woodward, F.I. 1998. Net primary and ecosystem production and carbon stocks of terrestrial ecosystems and their responses to climate change. *Global Change Biology*, 4: 185–198.
- Chertov, O.G., Komarov, A.S., Nadporozhskaya, M., Bykhovets, S.S. & Zudin, S.L. 2001. ROMUL – a model of forest soil organic matter dynamics as a substantial tool for forest ecosystem modelling. *Ecological Modelling*, 138: 289–308.
- Coleman, K. & Jenkinson, D.S. 1996. RothC-26.3. A model for the turnover of carbon in soil. In D.S. Powlson, P. Smith & J.U. Smith, eds. *Evaluation of soil organic matter models using existing long-term datasets*, pp. 237–246. NATO ASI Series I, Vol. 38. Heidelberg, Springer-Verlag.
- Conen, F., Yakutin, M.V. & Sambuu, A.D. 2003. Potential for detecting changes in soil organic carbon concentrations resulting from climate change. *Global Change Biology*, 9: 1515–1520.
- Eckersten, H. & Beier, C. 1998. Comparison of N and C dynamics in two Norway spruce stands using a process-oriented simulation model. *Environmental Pollution*, 102: 395–401.
- Eswaran, H., van den Berg, E. & Reich, P. 1993. Organic carbon in soils of the world. *Soil Science Society of America J.*, 57: 192–194.
- FAO. 1995. *Global and national soils and terrain digital databases (SOTER)*. Rome, Food and Agriculture Organization of the United Nations.
- FAO. 2006. *World reference base for soil resources 2006. A framework for international classification, correlation and communication*. Rome, FAO.
- FAO/IIASA/ISRIC/ISSCAS/JRC. 2008. *Harmonized World Soil Database (version 1.0)*. Rome, FAO and Laxenburg, Austria, IIASA.
- Häkkinen, M., Heikkinen, J. & Mäkipää, R. 2011. Soil carbon stock increases in the organic layer of boreal middle-aged stands. *Biogeosciences*, 8: 1279–1289.
- Henry, M., Valentini, R. & Bernoux, M. 2009. Soil carbon stocks in ecoregions of Africa. *Biogeosciences Discuss.*, 6: 797–823.
- IPCC. 2000. *Land use, land-use change and forestry*. IPCC Special Report. United Kingdom, Cambridge University Press.
- IPCC. 2003. *Good practice guidance for land use, land-use change and forestry*. Kanagawa, Japan, National Greenhouse Gas Inventories Programme.

- IPCC. 2006. *Guidelines for national greenhouse gas inventories*. Kanagawa, Japan, National Greenhouse Gas Inventories Programme.
- Jobbágy, E.G. & Jackson, R.B. 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, 10: 423–436.
- Kurz, W.A., Apps, M.J., Webb, T.M. & McNamee, P.J. 1992. *The carbon budget of the Canadian forest sector: Phase I*. Information Report NOR-X-326. Edmonton, Alberta, Forestry Canada, Northwest Region.
- Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C.E., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J.M. & Apps, M.J. 2009. CBM-CFS3: a model of carbon dynamics in forestry and land-use change implementing IPCC standards. *Ecological Modelling*, 220(4): 480–504.
- Lagergren, F., Grelle, A., Lankreijer, H., Mölder, M. & Lindroth, A. 2006. Current carbon balance of the forested area in Sweden and its sensitivity to global change as simulated by Biome-BGC. *Ecosystems*, 9(6): 894–908.
- Liski, J., Lehtonen, A., Palosuo, T., Peltoniemi, M., Eggers, T., Muukkonen, P. & Mäkipää, R. 2006. Carbon accumulation in Finland's forests 1922–2004 – an estimate obtained by combination of forest inventory data with modelling of biomass, litter and soil. *Annals of Forest Sci.*, 63(7): 687–697.
- Liski, J., Palosuo, T., Peltoniemi, M. & Sievänen, R. 2005. Carbon and decomposition model Yasso for forest soils. *Ecological Modelling*, 189: 168–182.
- Liski, J., Perruchoud, D. & Karjalainen, T. 2002. Increasing carbon stocks in the forest soils of western Europe. *Forest Ecology and Management*, 169: 159–175.
- Mäkipää, R., Häkkinen, M., Muukkonen, P. & Peltoniemi, M. 2008. The costs of monitoring changes in forest soil carbon stocks. *Boreal Environment Res.*, 13: 120–130.
- Malhi, Y. & Grace, J. 2000. Tropical forests and atmospheric carbon dioxide. *Trends in Ecology & Evolution*, 15(8): 332–337.
- Munishi, P.K.T. & Shear, T.H. 2004. Carbon storage in afro-montane rain forests of the eastern arc mountains of Tanzania: their net contribution to atmospheric carbon. *J. Tropical Forest Sci.*, 16: 78–93.
- Muukkonen, P., Häkkinen, M. & Mäkipää, R. 2009. Spatial variation in soil carbon in the organic layer of managed boreal forest soil – implications for sampling design. *Environmental Monitoring and Assessment*, 158: 67–76.
- NAFORMA. 2010. *National forestry resources monitoring and assessment (NAFORMA) of Tanzania. Field Manual. Biophysical Survey*. Document M01-2010. United Republic of Tanzania, Ministry of Natural Resources & Tourism.
- Ogle, S.M. & Paustian, K. 2005. Soil organic carbon as an indicator of environmental quality at the national scale: inventory monitoring methods and policy relevance. *Canadian J. Soil Science*, 85: 531–540.
- Pan, Y., Birdsey, R., Fang, J. *et al.* 2011. A large and persistent carbon sink in the world's forests. *Science*, 333: 988–993.
- Parton, W.J., Schimel, D.S., Cole, C.V. & Ojima, D.S. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Society of America J.*, 51: 1173–1179.

- Peltoniemi, M., Heikkinen, J. & Mäkipää, R. 2007. Stratification of regional sampling by model-predicted changes of carbon stocks in forested mineral soils. *Silva Fennica*, 41(3): 527–539.
- Peltoniemi, M., Mäkipää, R., Liski, J. & Tamminen, P. 2004. Changes in soil carbon with stand age – an evaluation of a modelling method with empirical data. *Global Change Biology*, 10(12): 2078–2091.
- Peltoniemi, M., Thürig, E., Ogle, S., Palosuo, T., Schrumpf, M., Wutzler, T., Butterbach-Bahl, K., Chertov, O., Komarov, A., Mikhailov, A., Gärdenäs, A., Perry, C., Liski, J., Smith, P. & Mäkipää, R. 2007. Models in country scale carbon accounting of forest soils. *Silva Fennica*, 41(3): 575–602.
- Peters, G.P., Marland, G., Le Quéré, C., Boden, T., Canadell, J.G., & Raupach, M.R. 2012. Rapid growth in CO<sub>2</sub> emissions after the 2008–2009 global financial crisis. *Nature Climate Change*, 2: 2–4.
- Post, W.M., Izaurralde, R.C., Mann, L.K. & Bliss, N. 2001. Monitoring and verifying changes of organic carbon in soil. *Climatic Change*, 51(1): 73–99.
- Post, W.M. & Kwon, K.C. 2000. Soil carbon sequestration and land-use change: processes and potential. *Global Change Biology*, 6: 317–327.
- Raich, J.W. & Schlesinger, W.H. 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus B*, 44(2): 81–99.
- Rossi, J., Govaerts, A., De Vos, B., Verbist, B., Vervoort, A., Poesen, J., Muys, B. & Deckers, J. 2009. Spatial structures of soil organic carbon in tropical forests – A case study of Southeastern Tanzania. *Catena*, 77: 19–27.
- Smith, P., Davies, C.A., Ogle, S., Zanchi, G., Bellarby, J., Bird, N., Boddey, R.M., McNamara, N.P., Powlson, D., Cowie, A., van Noordwijk, M., Davis, S.C., Richter, D.d., Kryzanowski, L., van Wijk, M.T., Stuart, J., Kirton, A., Eggar, D., Newton-Cross, G., Adhya, T.K. & Braimoh, A.K. 2012. Towards an integrated global framework to assess the impacts of land use and management change on soil carbon: current capability and future vision. *Global Change Biology*. First published online doi: 10.1111/j.1365-2486.2012.02689.x
- Solomon, D., Lehmann, J. & Zech, W. 2000. Land use effects on soil organic matter properties of chromic luvisols in semi-arid northern Tanzania: carbon, nitrogen, lignin and carbohydrates. *Agriculture, Ecosystems & Environment*, 78: 203–213.
- Sombroek, W., Nachtergaele, F.O. & Hebel, A. 1993. Amounts, dynamics and sequestering of carbon in tropical and subtropical soils. *Ambio*, 22: 417–426.
- Ståhl, G., Boström, B., Lindkvist, H., Lindroth, A., Nilsson, J. & Olsson, M. 2004. Methodological options for quantifying changes in carbon pools in Swedish forests. *Studia Forestalia Suecica*, 214: 1–46.
- Tamminen, P. 2003. Sampling and laboratory errors in forest soil analysis. *Communications in Soil Science and Plant Analysis*, 34: 1193–1209.
- Tamminen, P. & Derome, J. 2005. Temporal trends in chemical parameters of upland forest soils in southern Finland. *Silva Fennica*, 39(3): 313–330.
- Thum, T., Räisänen, P., Sevanto, S., Tuomi, M., Reick, C., Vesala, T., Raddatz, T., Aalto, T., Järvinen, H., Altimir, N., Pilegaard, K., Zoltan, N., Rambal, S. & Liski, J. 2011. Soil carbon model alternatives for ECHAM5/JSBACH climate model:

- evaluation and impacts on global carbon cycle estimates. *J. Geophysical Res. – Biogeosciences*, 116. doi: 10.1029/2010JG001612.
- Tomppo, E., Katila, M., Mäkisara, K., Peräsaari, J., Malimbwi, R., Chamuya, N., Otieno, J., Dalsgaard, S. & Leppänen, M.** 2010. *A Report to the Food and Agriculture Organization of the United Nations (FAO) in support of Sampling Study for National Forestry Resources Monitoring and Assessment (NAFORMA) in Tanzania*. Rome, FAO. <http://www.mp-discussion.org/NAFORMA.pdf/> (last accessed April 2012)
- Tuomi, M., Laiho, R., Repo, A. & Liski, J.** 2011a. Wood decomposition model for boreal forests. *Ecological Modelling*, 222 (3): 709–718.
- Tuomi, M., Rasinmäki, J., Vanhala, P., Repo, A. & Liski, J.** 2011b. Soil carbon model Yasso07 user interface. *Environmental Modelling and Software*, 26(11): 1358–1362.
- Tuomi, M., Thum, T., Järvinen, H., Fronzek, S., Berg, B., Harmon, M., Trofymow, J.A., Sevanto, S. & Liski, J.** 2009. Leaf litter decomposition – estimates of global variability based on Yasso07 model. *Ecological Modelling*, 220 (23): 3362–3371.
- Tuomi, M., Vanhala, P., Karhu, K., Fritze, H. & Liski, J.** 2008. Heterotrophic soil respiration – comparison of different models describing its temperature dependence. *Ecological Modelling*, 211(1): 182–190.
- Vågen, T.-G., Lal, R. & Singh, B.R.** 2005. Soil carbon sequestration in sub-Saharan Africa: a review. *Land Degradation & Development*, 16: 53–71.
- Wang, L., Okin, G.S., Caylor, K.K. & Macko, S.A.** 2009. Spatial heterogeneity and sources of soil carbon in southern African savannas. *Geoderma*, 149: 402–408.
- Yanai, R.D., Stehman, S., Arthur, M., Prescott, C., Friedland, A., Siccama, T. & Binkley, D.** 2003. Detecting change in forest floor carbon. *Soil Science Society of America J.*, 67: 1583–1593.
- Young, A., Menz, K., Muraya, P. & Smith, C.** 1998. *SCUAF Version 4 – a model to estimate soil changes under agriculture, agroforestry and forestry*. ACIAR Technical Reports Series No. 41. Canberra.
- Zingore, S., Manyame, C., Nyamugafata, P. & Giller, K.E.** 2005. Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe. *European J. Soil Sci.*, 56: 727–736.



## FAO TECHNICAL PAPERS

### FAO FORESTRY PAPERS

1	Forest utilization contracts on public land, 1977 (E F S)	18	Forest products prices 1960-1978, 1980 (E/F/S)
2	Planning forest roads and harvesting systems, 1977 (E F S)	19/1	Pulping and paper-making properties of fast-growing plantation wood species – Vol. 1, 1980 (E)
3	World list of forestry schools, 1977 (E/F/S)	19/2	Pulping and paper-making properties of fast-growing plantation wood species – Vol. 2, 1980 (E)
3 Rev.1	World list of forestry schools, 1981 (E/F/S)		
3 Rev.2	World list of forestry schools, 1986 (E/F/S)		
4/1	World pulp and paper demand, supply and trade – Vol. 1, 1977 (E F S)	20	Forest tree improvement, 1985 (C E F S)
4/2	World pulp and paper demand, supply and trade – Vol. 2, 1977 (E F S)	20/2	A guide to forest seed handling, 1985 (E S )
5	The marketing of tropical wood in South America, 1976 (E S)	21	Impact on soils of fast-growing species in lowland humid tropics, 1980 (E F S)
6	National parks planning, 1976 (E F S)	22/1	Forest volume estimation and yield prediction – Vol. 1. Volume estimation, 1980 (C E F S)
7	Forestry for local community development, 1978 (Ar E F S)	22/2	Forest volume estimation and yield prediction – Vol. 2. Yield prediction, 1980 (C E F S)
8	Establishment techniques for forest plantations, 1978 (Ar C E* F S)		
9	Wood chips – production, handling, transport, 1976 (C E S)	23	Forest products prices 1961-1980, 1981 (E/F/S)
10/1	Assessment of logging costs from forest inventories in the tropics – 1. Principles and methodology, 1978 (E F S)	24	Cable logging systems, 1981 (C E)
10/2	Assessment of logging costs from forest inventories in the tropics – 2. Data collection and calculations, 1978 (E F S)	25	Public forestry administrations in Latin America, 1981 (E)
11	Savanna afforestation in Africa, 1977 (E F)	26	Forestry and rural development, 1981 (E F S)
12	China: forestry support for agriculture, 1978 (E)	27	Manual of forest inventory, 1981 (E F)
13	Forest products prices 1960-1977, 1979 (E/F/S)	28	Small and medium sawmills in developing countries, 1981 (E S)
14	Mountain forest roads and harvesting, 1979 (E)	29	World forest products, demand and supply 1990 and 2000, 1982 (E F S)
14 Rev.1	Logging and transport in steep terrain, 1985 (E)	30	Tropical forest resources, 1982 (E F S)
15	AGRIS forestry – world catalogue of information and documentation services, 1979 (E/F/S)	31	Appropriate technology in forestry, 1982 (E)
16	China: integrated wood processing industries, 1979 (E F S)	32	Classification and definitions of forest products, 1982 (Ar/E/F/S)
17	Economic analysis of forestry projects, 1979 (E F S)	33	Logging of mountain forests, 1982 (E F S)
17 Sup.1	Economic analysis of forestry projects: case studies, 1979 (E S)	34	Fruit-bearing forest trees, 1982 (E F S)
17 Sup.2	Economic analysis of forestry projects: readings, 1980 (C E)	35	Forestry in China, 1982 (C E)
		36	Basic technology in forest operations, 1982 (E F S)
		37	Conservation and development of tropical forest resources, 1982 (E F S)
		38	Forest products prices 1962-1981, 1982 (E/F/S)
		39	Frame saw manual, 1982 (E)
		40	Circular saw manual, 1983 (E)
		41	Simple technologies for charcoal making, 1983 (E F S)

42	Fuelwood supplies in the developing countries, 1983 (Ar E F S)	62	World list of institutions engaged in forestry and forest products research, 1985 (E/F/S)
43	Forest revenue systems in developing countries, 1983 (E F S)	63	Industrial charcoal making, 1985 (E)
44/1	Food and fruit-bearing forest species – 1. Examples from eastern Africa, 1983 (E F S)	64	Tree growing by rural people, 1985 (Ar E F S)
44/2	Food and fruit-bearing forest species – 2. Examples from southeastern Asia, 1984 (E F S)	65	Forest legislation in selected African countries, 1986 (E F)
44/3	Food and fruit-bearing forest species – 3. Examples from Latin America, 1986 (E S)	66	Forestry extension organization, 1986 (C E S)
45	Establishing pulp and paper mills, 1983 (E)	67	Some medicinal forest plants of Africa and Latin America, 1986 (E)
46	Forest products prices 1963-1982, 1983 (E/F/S)	68	Appropriate forest industries, 1986 (E)
47	Technical forestry education – design and implementation, 1984 (E F S)	69	Management of forest industries, 1986 (E)
48	Land evaluation for forestry, 1984 (C E F S)	70	Wildland fire management terminology, 1986 (E/F/S)
49	Wood extraction with oxen and agricultural tractors, 1986 (E F S)	71	World compendium of forestry and forest products research institutions, 1986 (E/F/S)
50	Changes in shifting cultivation in Africa, 1984 (E F)	72	Wood gas as engine fuel, 1986 (E S)
50/1	Changes in shifting cultivation in Africa – seven case-studies, 1985 (E)	73	Forest products: world outlook projections 1985-2000, 1986 (E/F/S)
51/1	Studies on the volume and yield of tropical forest stands – 1. Dry forest formations, 1989 (E F)	74	Guidelines for forestry information processing, 1986 (E)
52/1	Cost estimating in sawmilling industries: guidelines, 1984 (E)	75	Monitoring and evaluation of social forestry in India – an operational guide, 1986 (E)
52/2	Field manual on cost estimation in sawmilling industries, 1985 (E)	76	Wood preservation manual, 1986 (E)
53	Intensive multiple-use forest management in Kerala, 1984 (E F S)	77	Databook on endangered tree and shrub species and provenances, 1986 (E)
54	Planificación del desarrollo forestal, 1984 (S)	78	Appropriate wood harvesting in plantation forests, 1987 (E)
55	Intensive multiple-use forest management in the tropics, 1985 (E F S)	79	Small-scale forest-based processing enterprises, 1987 (E F S)
56	Breeding poplars for disease resistance, 1985 (E)	80	Forestry extension methods, 1987 (E)
57	Coconut wood – Processing and use, 1985 (E S)	81	Guidelines for forest policy formulation, 1987 (C E)
58	Sawdoctoring manual, 1985 (E S)	82	Forest products prices 1967-1986, 1988 (E/F/S)
59	The ecological effects of eucalyptus, 1985 (C E F S)	83	Trade in forest products: a study of the barriers faced by the developing countries, 1988 (E)
60	Monitoring and evaluation of participatory forestry projects, 1985 (E F S)	84	Forest products: World outlook projections – Product and country tables 1987-2000, 1988 (E/F/S)
61	Forest products prices 1965-1984, 1985 (E/F/S)	85	Forestry extension curricula, 1988 (E/F/S)
		86	Forestry policies in Europe, 1988 (E)
		87	Small-scale harvesting operations of wood and non-wood forest products involving rural people, 1988 (E F S)

88	Management of tropical moist forests in Africa, 1989 (E F P)	112	Forest resources assessment 1990 – Tropical countries, 1993 (E)
89	Review of forest management systems of tropical Asia, 1989 (E)	113	Ex situ storage of seeds, pollen and in vitro cultures of perennial woody plant species, 1993 (E)
90	Forestry and food security, 1989 (Ar E S)	114	Assessing forestry project impacts: issues and strategies, 1993 (E F S)
91	Design manual on basic wood harvesting technology, 1989 (E F S) (Published only as FAO Training Series, No. 18)	115	Forestry policies of selected countries in Asia and the Pacific, 1993 (E)
92	Forestry policies in Europe – An analysis, 1989 (E)	116	Les panneaux à base de bois, 1993 (F)
93	Energy conservation in the mechanical forest industries, 1990 (E S)	117	Mangrove forest management guidelines, 1994 (E)
94	Manual on sawmill operational maintenance, 1990 (E)	118	Biotechnology in forest tree improvement, 1994 (E)
95	Forest products prices 1969-1988, 1990 (E/F/S)	119	Number not assigned
96	Planning and managing forestry research: guidelines for managers, 1990 (E)	120	Decline and dieback of trees and forests – A global overview, 1994 (E)
97	Non-wood forest products: the way ahead, 1991 (E S)	121	Ecology and rural education – Manual for rural teachers, 1995 (E S)
98	Timber plantations in the humid tropics of Africa, 1993 (E F)	122	Readings in sustainable forest management, 1994 (E F S)
99	Cost control in forest harvesting and road construction, 1992 (E)	123	Forestry education – New trends and prospects, 1994 (E F S)
100	Introduction to ergonomics in forestry in developing countries, 1992 (E F I)	124	Forest resources assessment 1990 – Global synthesis, 1995 (E F S)
101	Management and conservation of closed forests in tropical America, 1993 (E F P S)	125	Forest products prices 1973-1992, 1995 (E F S)
102	Research management in forestry, 1992 (E F S)	126	Climate change, forests and forest management – An overview, 1995 (E F S)
103	Mixed and pure forest plantations in the tropics and subtropics, 1992 (E F S)	127	Valuing forests: context, issues and guidelines, 1995 (E F S)
104	Forest products prices 1971-1990, 1992 (E/F/S)	128	Forest resources assessment 1990 – Tropical forest plantation resources, 1995 (E)
105	Compendium of pulp and paper training and research institutions, 1992 (E)	129	Environmental impact assessment and environmental auditing in the pulp and paper industry, 1996 (E)
106	Economic assessment of forestry project impacts, 1992 (E/F)	130	Forest resources assessment 1990 – Survey of tropical forest cover and study of change processes, 1996 (E)
107	Conservation of genetic resources in tropical forest management – Principles and concepts, 1993 (E/F/S)	131	Ecología y enseñanza rural – Nociones ambientales básicas para profesores rurales y extensionistas, 1996 (S)
108	A decade of wood energy activities within the Nairobi Programme of Action, 1993 (E)	132	Forestry policies of selected countries in Africa, 1996 (E/F)
109	Directory of forestry research organizations, 1993 (E)	133	Forest codes of practice – Contributing to environmentally sound forest operations, 1996 (E)
110	Proceedings of the Meeting of Experts on Forestry Research, 1993 (E/F/S)	134	Estimating biomass and biomass change of tropical forests – A primer, 1997 (E)
111	Forestry policies in the Near East region – Analysis and synthesis, 1993 (E)		

135	Guidelines for the management of tropical forests – 1. The production of wood, 1998 (E S)	154	Forests and energy – Key issues, 2008 (Ar C E F R S)
136	Managing forests as common property, 1998 (E)	155	Forests and water, 2008 (E F S)
137/1	Forestry policies in the Caribbean – Volume 1: Proceedings of the Expert Consultation, 1998 (E)	156	Global review of forest pests and diseases, 2009 (E)
137/2	Forestry policies in the Caribbean – Volume 2: Reports of 28 selected countries and territories, 1998 (E)	157	Human-wildlife conflict in Africa – Causes, consequences and management strategies, 2009 (E F)
138	FAO Meeting on Public Policies Affecting Forest Fires, 2001 (E F S)	158	Fighting sand encroachment – Lessons from Mauritania, 2010 (E F)
139	Governance principles for concessions and contacts in public forests, 2003 (E F S)	159	Impact of the global forest industry on atmospheric greenhouse gases, 2010 (E)
140	Global Forest Resources Assessment 2000 – Main report, 2002 (E F S)	160	Criteria and indicators for sustainable woodfuels, 2010 (E)
141	Forestry Outlook Study for Africa – Regional report: opportunities and challenges towards 2020, 2003 (Ar E F)	161	Developing effective forest policy - A guide, 2010 (E F S)
142	Cross-sectoral policy impacts between forestry and other sectors, 2003 (E F S)	162	What woodfuels can do to mitigate climate change, 2010 (E)
143	Sustainable management of tropical forests in Central Africa – In search of excellence, 2003 (E F)	163	Global Forest Resources Assessment 2010 - Main report (Ar C E F R S)
144	Climate change and the forest sector – Possible national and subnational legislation, 2004 (E)	164	Guide to implementation of phytosanitary standards in forestry, 2011 (C E F R)
145	Best practices for improving law compliance in the forest sector, 2005 (E F R S)	165	Reforming forest tenure – Issues, principles and process, 2011 (E S)
146	Microfinance and forest-based small-scale enterprises, 2005 (Ar E F S)	166	Community-based fire management – A review (E)
147	Global Forest Resources Assessment 2005 – Progress towards sustainable forest management, 2006 (E F S)	167	Wildlife in a changing climate (E)
148	Tendencias y perspectivas del sector forestal en América Latina y el Caribe, 2006 (S)	168	Soil carbon monitoring using surveys and modelling - General description and application in the United Republic of Tanzania (E)
149	Better forestry, less poverty – A practitioner's guide, 2006 (Ar E F S)		
150	The new generation of watershed management programmes and projects, 2006 (E F S)		
151	Fire management – Global assessment 2006, 2007 (E)		
152	People, forests and trees in West and Central Asia – Outlook for 2020, 2007 (Ar E R)		
153	The world's mangroves 1980–2005, 2007 (E)		

Ar – Arabic	Multil – Multilingual
C – Chinese	* – Out of print
E – English	
I – Italian	
F – French	
P – Portuguese	
S – Spanish	
R – Russian	

*The FAO Technical Papers are available through the authorized FAO Sales Agents or directly from Sales and Marketing Group, FAO, Viale delle Terme di Caracalla, 00153 Rome, Italy.*